3

PHYSICAL SCI. LIB.

ENGINEERING GEOLOGY OF THE GEYSERS GEOTHERMAL RESOURCE AREA

Lake, Mendocino, and Sonoma Counties, California

1976

CALIFORNIA DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 122

UNIVERSITY OF CALIFORNIA
DAVIS
APR 2 3 1976
GOV'T. DOCS. - LIBRARY

Special Report 122

ENGINEERING GEOLOGY OF THE GEYSERS GEOTHERMAL RESOURCE AREA
Lake, Mendocino, and Sonoma Counties, California

By

C. Forrest Bacon, Perry Y. Amimoto,
Roger W. Sherburne, and James E. Slosson

California Division of Mines and Geology
1416 Ninth Street, Room 1341
Sacramento CA 95814

This report was completed in February 1974. Work completed since that time is included in the first part of the introduction and in Appendices 1 through 5 . Appendix 1 is U.S. Geological Survey Open File Map 74-238, *Preliminary geologic map of The Geysers steam field and vicinity, Sonoma County, California*, by Robert J. McLaughlin; geothermal well locations were added by CDMG. All photos are by C. Forrest Bacon.

STATE OF CALIFORNIA
EDMUND G. BROWN JR., *GOVERNOR*

THE RESOURCES AGENCY
CLAIRE T. DEDRICK, *SECRETARY FOR RESOURCES*

DEPARTMENT OF CONSERVATION
LEWIS A. MORAN, *DIRECTOR*

DIVISION OF MINES AND GEOLOGY
THOMAS E. GAY, JR., *ACTING STATE GEOLOGIST*

CONTENTS

INTRODUCTION 5
  Purpose and Scope 5
  General Geology 5
  Sources of Geologic Information 7
GEOLOGIC UNITS 7
  Franciscan Assemblage 7
  Great Valley Sequence 8
  Martinez and Tejon Formations 8
  Merced Formation 9
  Cache Formation 9
  Sonoma Volcanics 9
  Clear Lake Volcanic Rocks 9
  Terrace Deposits 10
  Quaternary Alluvium 10
GEOLOGIC STRUCTURE 10
LANDSLIDES 11
SEISMICITY 11
MINERAL RESOURCES 14
ENGINEERING GEOLOGY 14
  Landslides 14
  Erosion Control 14
  Liquid Waste Disposal 18
  Expansive Soils 18
  Ground-Water Contamination 18
  Seismic and Subsidence Measures 18
RECOMMENDED MITIGATING MEASURES 18
  1. Procedures Regarding Landslides 18
  2. Procedures Regarding Erosion Control 18
  3. Procedures Regarding Liquid Waste Disposal 21
  4. Procedures Regarding Expansive Soil 21
  5. Procedures Regarding Ground-Water Contamination 21
  6. Procedures Regarding Soil Engineering and Engineering Geology Investigations 21
  7. Procedures for Monitoring Earthquake Activity 21
REFERENCES 23

Appendices

1. Preliminary geologic map of The Geysers steam field and vicinity, Sonoma County, with geothermal well locations ..... 24, In pocket
2. CDMG Notes 37 "Guidelines to geologic/seismic reports"; 43 "Recommended guidelines for determining the maximum credible and the maximum probable earthquakes"; 44 "Recommended guidelines for preparing engineering geologic reports"; 46 "Guidelines for geologic/seismic considerations in environmental impact reports" 25
3. Proposed revision of geothermal regulations 32
4. Blowout of a geothermal well at The Geysers Geothermal Field, Sonoma County, California 33
5. Recommended certification block for engineering geology and soils engineering reports 35

ILLUSTRATIONS

Figure 1. Index map showing outline of The Geysers Geothermal Resource Area, physiographic zones, and U.S. Geological Survey 15-minute quadrangles 4
Figure 2. Geologic map of The Geysers Geothermal Resource Area 6
Figure 3. Cross section of Big Sulphur Creek fault zone 13
Figure 4. Suggested checklist for review of environmental impact reports for geologic hazards at geothermal well facilities 22

Photo 1. Large inclusions from a Franciscan melange unit resting at the base of a slide along Big Sulphur Creek 12
Photo 2. Franciscan melange exposed in cut-slope above a power plant retaining wall 12
Photo 3. Slide caused by undercutting of slope at back of drill site 12
Photo 4. Erosion and sliding has occurred on benches excavated for geothermal well drilling operations 15
Photo 5. Slide on a hillside above a geothermal well site. View from dump of old mercury mining operation (well head is behind steam cloud) 15
Photo 6. An example of landslide encroachment on a power plant site 15
Photo 7. Another power plant with a situation similar to that illustrated in photo 6 16
Photo 8. Slumping and erosion at well site associated with uncompacted, nonengineered fill 16
Photo 9. Drill sump contents were mixed with the nonengineered fill material to build road, with slumping and erosion resulting from instability of materials 16
Photo 10. Inadequate drainage has been a major factor causing slumping 17
Photo 11. Slumping and erosion have occurred in nonengineered fill material mixed with drill sump contents near a well site 17
Photo 12. Hay used as a filter for rainfall to control erosion on slopes at this drill site 17
Photo 13. Hay used for a mulch over this planted slope near a power plant 17
Photo 14. Drill site constructed over a spring; ensuing erosion was caused by inadequate drainage 19
Photo 15. A road at the edge of a drill site has slumped and eroded due to inadequate drainage 19
Photo 16. "Baker tanks" were used here to replace cut-and-fill type sumps 19
Photo 17. Well sited on a hydrothermally altered landslide area 20
Photo 18. At this well site 70± feet of material were removed to replace damaged casing 20

Table 1. Preliminary analysis of geothermal facilities on unstable terrain, The Geysers 7

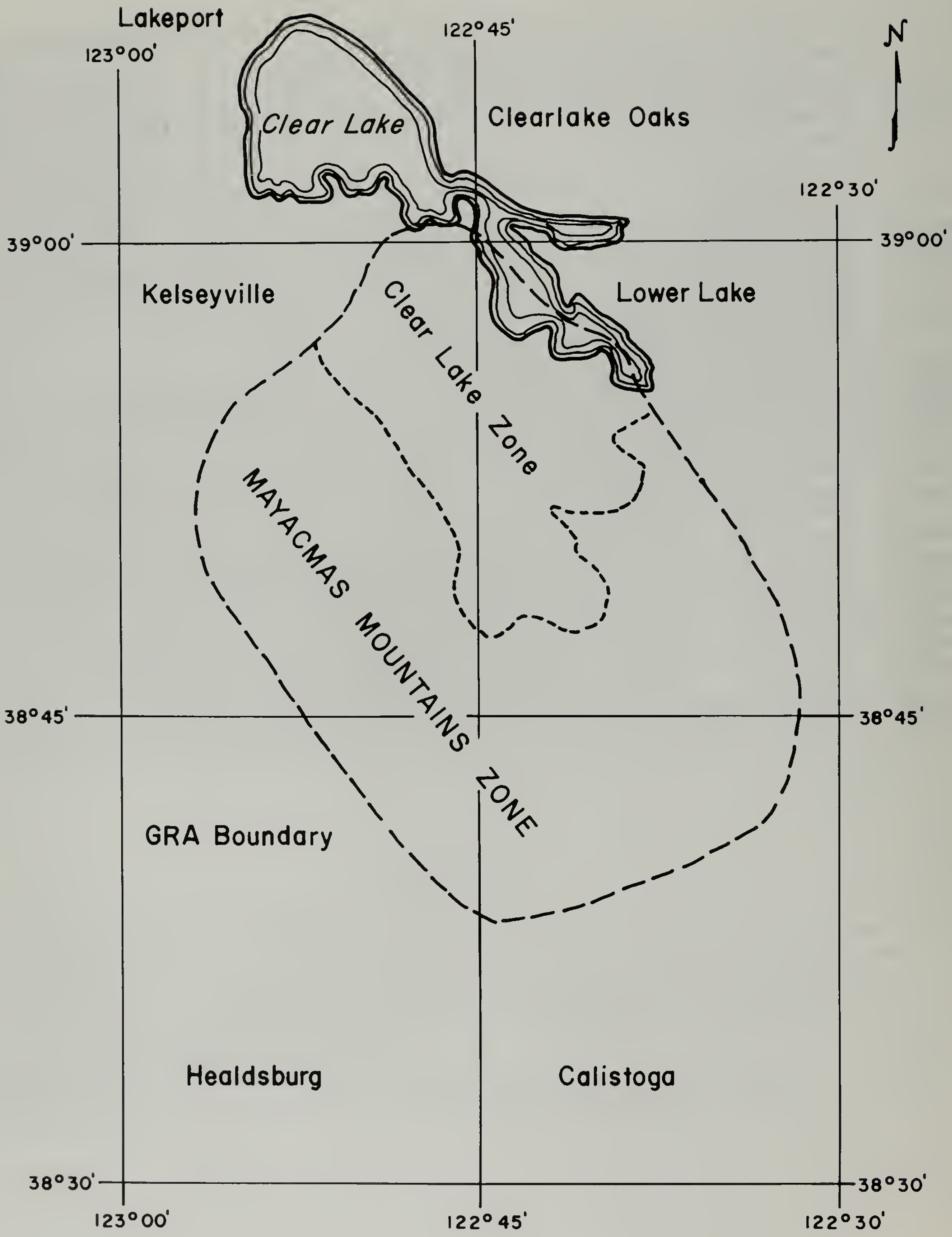


Figure 1. Index map showing outline of The Geysers Geothermal Resource Area, physiographic zones, and U.S. Geological Survey 15 minute quadrangles.

Engineering Geology of The Geysers Geothermal Resource Area, Lake, Mendocino, and Sonoma Counties, California

By C. Forrest Bacon[1], Perry Y. Amimoto[1], Roger W. Sherburne[2], and James E. Slosson[1]

INTRODUCTION

The blowout on March 31, 1975, of the Union Oil Company geothermal well "GDC" 65-28, which was situated on a landslide and may have been affected by reactivation of the landslide, motivated an analysis of the number and percentage of geothermal wells that have been sited on landslides. The preliminary analysis given in table 1 indicates that, within the area mapped by McLaughlin (1974), 91 of the 168 wells plotted have been sited on landslides. It seems imperative that a complete well-by-well assessment of the geologic conditions, as well as any hazardous conditions that may exist or may occur, should be made throughout The Geysers area. This should be done for all wells in the area and should be followed by appropriate remedial acion by the operator, including possible abandonment of certain wells where critical geologic conditions, or the expense involved in repair, make renovation of the well impracticable.

The potential earthquake activity referred to under the heading "Seismology" could reactivate and/or initiate landslides that could cause damage to facilities such as power plants and geothermal wells. Such facilities should either be sited to avoid landslides or be designed to withstand the possible adverse effects. The February 9, 1971, San Fernando earthquake triggered more than 1000 landslides.

Adverse effects that may be experienced with geothermal development can be mitigated or abated f good engineering geology and engineering practices are followed. Both public agencies and industry should be involved so that adequate standards, policies, and enforcement are adopted to prevent detrimental environmental and economic effects.

Applicable cost benefits appear to be weighted heavily in favor of doing the job properly the first time rather than attempting to correct a disaster.

Purpose and Scope

This report provides guidelines for the engineering geology assessment of The Geysers Geothermal Resource Area (GRA). Approximately 50 percent of the geothermal wells and some of the power plants are presently located on landslide areas. Several geothermal wells have failed, causing additional land instability, loss of energy resource, and unnecessary expense.

Hazardous geologic conditions in the area are identified, and measures for mitigating those hazardous conditions are recommended. Such measures or other equally adequate measures should be considered for any proposed development activity in The Geysers area.

General Geology

The geologic framework for The Geysers GRA is characterized by a series of northwest-trending folded and faulted blocks and thrust plates. The Geysers GRA can be divided into two major physiographic zones: The Mayacmas Mountains zone, including the Harbin Mountain-Middletown area, and the Clear Lake zone, including the Clear Lake-Boggs Mountain-Cobb Mountain volcanic area (figure 1).

The Mayacmas Mountains zone is typically broken into a series of northwest-trending ridges and valleys corresponding to the trend of the structural framework for the area, while the Clear Lake zone is typified by a series of domes, cones, and flows that display generally rounded patterns. The engineering geology characteristics of each of the zones also differ according to the rock types present in each zone.

In the Mayacmas Mountains zone, the Great Valley sequence of Jurassic to Cretaceous marine miogeosynclinal sedimentary rocks and underlying igneous rocks are in thrust fault contact with, and overlie the rocks of, the eugeosynclinal Franciscan assemblage of similar age (figure 2). Also present in this zone are marine sedimentary rocks of Tertiary age southeast of Clear Lake, the Sonoma Volcanics of Pliocene age near Mount St. Helena, and scattered exposures of non-marine sedimentary rocks of Pliocene to Holocene age.

In the Clear Lake zone, Pleistocene volcanic rocks, ranging in type from rhyolite and obsidian to andesite, overlie the eroded surfaces of Franciscan rocks and rocks of the Great Valley sequence. The magmatic source from which these volcanic rocks were derived now apparently supplies the heat for the geothermal phenomena present throughout most of the area. A major area of anomalously low gravity, centered in the outcrop area of the Clear Lake volcanic rocks, has been interpreted as indicating the presence of a still-heated magma chamber by Chapman (1975).

---

[1] Geologist

[2] Seismologist

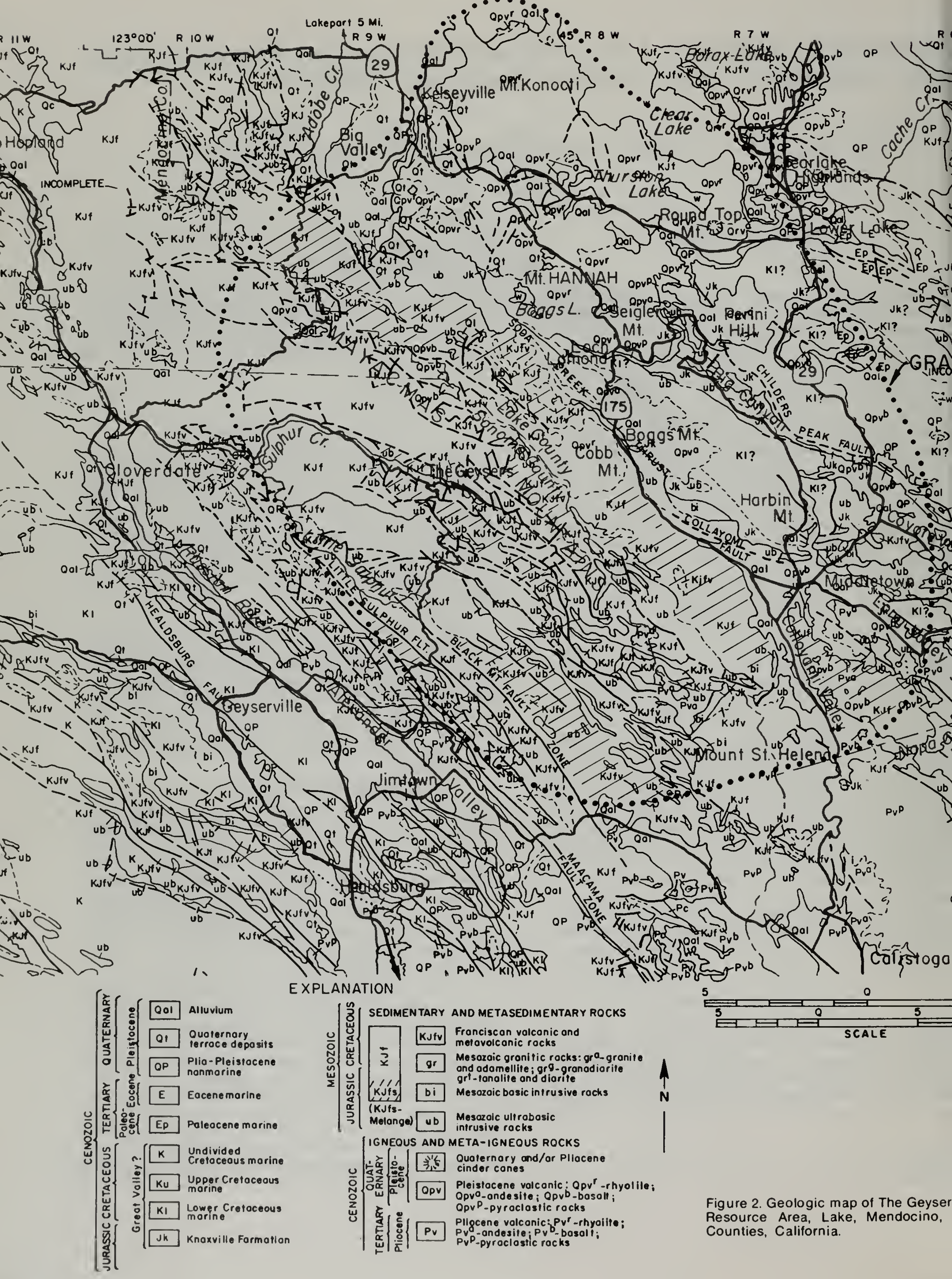


Figure 2. Geologic map of The Geyser
Resource Area, Lake, Mendocino,
Counties, California.

able 1. Preliminary analysis of geothermal facilities on unstable terrain, The eysers, Lake, Sonoma, and Mendocino Counties, California.

POWER PLANTS

ocation of power plant	*Plant number*	*Type of terrain at site*
W¼ sec. 19, T11N, R8W	1, 2	Partly on a slide.
W¼ sec. 13, T11N, R9W	3, 4	Entirely on a slide.
E¼ sec. 13, T11N, R9W	5, 6	On greenstone and altered melange with a slide encroaching.
½ sec. 13, T11N, R8W	9, 10	On Franciscan graywacke with minor shale and conglomerate.
W¼ sec. 7, T11N, R8W	11	On melange and greenstone.
E¼ sec. 18, T11N, R8W	12	On sedimentary breccia very close to a slide.

GEOTHERMAL WELLS

*Location of well**	*Total wells in sec.*	*Wells on landslide*
Sec. 6, T11N, R8W	7	3
Sec. 7	14	9
Sec. 17	4	2
Sec. 18	14	4
Sec. 19	1	0
Sec. 20	14	1
Sec. 26	6	1
Sec. 27	3	1
Sec. 28	3	3
Sec. 29	1	0
Sec. 30	1	0
Sec. 33	2	2
Sec. 34	2	1
Sec. 35	1	0
Sec. 1, T11N, R9W	6	4
Sec. 10	1	1
Sec. 11	9	7
Sec. 12	28	17
Sec. 13	30	26
Sec. 14	20	8
Sec. 35, T12N, R9W	1	1
Totals	168	91

*Well locations obtained from California Division of Oil and Gas Map G6-1, Union Oil Company maps, and *Munger Oilogram*. Geology from mapping by McLaughlin (1974).

Sources of Geologic Information

The geologic data used for this report have been ompiled mainly from published and unpublished eports and some field reconnaissance.

The following quadrangles and maps were used n the geologic study:

QUADRANGLE OR MAP	REFERENCE
alistoga (1:62,500).....	Bailey (1946)
	Yates and Hilpert (1946)
ealdsburg (1:62,500)....	Gealey (1951)
	Blake and others (1971)
elseyville-Mayacmas tns. area (1:62,500)....	McNitt (1968a)
	Blake and others (1971)
akeport (1:62,500)......	McNitt (1968b)
ower Lake (1:62,500)....	Brice (1953)
	Swe Dickinson (1970)
anta Rosa (1:250,000)...	Koenig (1963)
kiah (1:250,000)........	Jennings and Strand (1960)
he Geysers (1:24,000)...	McLaughlin (1974)

GEOLOGIC UNITS

Franciscan Assemblage

Rock units assigned to the Franciscan assemblage by Blake and others (1971) occur in major portions of The Geysers GRA mainly in the Mayacmas Mountains. The map data used for this report generally follows that of McNitt (1968a, b) with local modifications.

The Franciscan assemblage contains an abundance of sheared rock characterized by high clay content, low permeability, and by large numbers of landslides. The entire assemblage can be divided into three major rock units that are separated by faulting into three thrust plates. The unit which is most subject to sliding is exposed over major parts of the area, particularly in the vicinity of The Geysers GRA. This unit is the sheared shale and sandstone (KJfs) of Blake and others (1971) which contains resistant masses of hard rocks of several lithologic types. It corresponds to McNitt's Lower Jurassic-Cretaceous unit. Most of the sheared rock in the Franciscan assemblage, together with masses of shattered sandstone, is assigned to this unit. The term "melange" has been applied to Franciscan rocks of similar characteristics by Hsu (1969).

A melange unit generally consists of a highly sheared lustrous gray to black shale matrix containing abundant hard, resistant blocks of metagraywacke type sandstone, chert, greenstone, serpentinite, and metamorphic rock (photos 1,2). Size of the blocks ranges from less than 1 foot (30 cm) to greater than 5 miles (8 km) in length. They make up a highly variable proportion of the entire unit. The deleterious engineering properties of the melange unit are discussed in more detail under the heading "Engineering Geology".

The second of the three subdivisions of the Franciscan rocks, and the most stable for engineering purposes, consists principally of metagraywacke sandstone with lesser amounts of other metamorphic constituents, including metagreenstone and metachert. This unit is characterized by blueschist minerals, such as glaucophane, lawsonite, and jadeitic pyroxene. The main outcrop area lies near the southwestern margin of the GRA opposite Geyserville and Jimtown.

The third Franciscan unit corresponds to McNitt's "upper unit, Jurassic-Cretaceous", and has widespread outcrops in The Geysers GRA, particularly west and north of the present The Geysers geothermal development. It consists predominantly of graywacke-type sandstone and shale with minor greenstone, limestone, and chert and some lenses of conglomerate. The sandstone ranges from massive to thin bedded, but the rock is frequently shattered and commonly veined with laumontite and is subject to landslide activity.

The base of the Franciscan assemblage has not been recognized and no older formations are exposed. It is probable that the Franciscan rocks were deposited upon a thin oceanic crust and were emplaced in their present position as the Pacific plate slid beneath the North American continental plate.

Several rock types occur as discrete masses within the Franciscan units, and their presence can often serve as an indication of the melange-like character of the unit within which they occur. They include high grade metamorphic rocks, such as glaucophane schist, eclogite, and amphibolite; blocks of graywacke and metagraywacke sandstone; chert and metachert; greenstone, serpentinite, and silica-carbonate rock. Many of the high-grade metamorphic rock inclusions occur in blocks less than 100 feet (30 m) long. The three most important rock types are greenstone, serpentinite, and silica-carbonate rock.

Greenstone: These altered mafic submarine volcanic rocks include gray to greenish-gray spilitic basalts in the form of pillow lavas, massive flow rock, tuffs, and breccias. In many parts of the area, they occur as discrete masses no more than a few hundred feet thick, but McNitt (1968) has estimated a thickness of 7000 feet for the massive pile that trends northwestward for several miles from the vicinity of The Geysers Resort. In some places these rocks contain minor amounts of fossiliferous limestone; in others the greenstone contains in cipient blueschist minerals or is reconstituted t blueschist. Landslide activity, although not a prevalent as in some other rock units, does occur i the larger greenstone outcrop areas.

Serpentinite, including relatively fresh ultramafi masses "intrudes" the lower or melange unit of th Franciscan assemblage and occurs as sheets, lenses and irregular shaped masses, both within and alon the boundaries of the unit. Depending on the degre of internal shearing and alteration, serpentinite ca present foundation problems for engineered struc tures.

Silica-carbonate rock, a product of the alteration o serpentinite, can be a relatively hard and stron rock. It most often occurs in blocks and masse associated with serpentinite.

Great Valley Sequence

The Jurassic and Cretaceous Great Valle sequence consists mainly of well-bedded sandston and shale, massive shale and siltstone or mudston with minor sandstone, and conglomerate lenses an beds. Swe and Dickinson (1970), in their studie centered in the Lower Lake quadrangle, hav described 35,000 feet of clastic sedimentary strata ranging in age from Late Jurassic to Lat Cretaceous, as belonging to the Great Valle sequence. They have divided the entire sequenc stratigraphically into four main segments, three o which, although broken by faults, are apparentl conformable successions of strata. The fourth con sists of several segments of similar age each boun ded entirely by faults.

These rocks, with the exception of the shales generally do not present major engineerin problems. The shales, however, are particularl vulnerable to sliding where they abut a steep out crop of another rock type, such as serpentinite, o where the soil has been removed or they have bee undercut.

Ultramafic rocks, largely pyroxenite and ser pentinite, basaltic pillow lavas and breccias, quart diorite, diorite, gabbro, and diabase are presen locally at the base of the Great Valley sequence These rocks are in fault contact with the Francisca rocks. Their main association with instability o landsliding appears to be involved with slides in th Great Valley shales where the latter abut agains igneous rocks with high topographic relief.

Martinez and Tejon Formations

Rocks of the Paleocene Martinez Formation ar present in a synclinal trough at the lower end o Clear Lake near the town of Lower Lake. They ar also present in exposures 3 to 4 miles south o Lower Lake in Excelsior and Little High Valleys They overlie the Cretaceous rocks with angular un conformity. Lithologically these marine strata rang from a mudstone or shale in the northernmost ex sures to massive, white, coarse-grained sandstone nderlain by fine-grained, light-brown sandstone in e southern exposures.

White conglomeratic sandstone of the marine ocene Tejon Formation overlies the Martinez For- ation only in the northern exposure area east of ower Lake. Brice (1953) estimated a variable ickness from 2200 to 4200 feet for the Martinez ormation in this area. A brown sandstone unit that rice included with the undifferentiated Cretaceous cks has since been placed by Swe and Dickinson 970) in the lowermost part of the Martinez For- ation based on fossil evidence. The thickness of e entire Lower Tertiary sequence, including ocene and Paleocene rocks, is about 5500 feet. ngineering properties of these formations are riable depending largely on the degree of cemen- tion in the sandstone and upon moisture content, d undercutting, or soil removal in the shales. versteepening of slopes, adverse bedding, and egree of fracturing can also create major gineering problems.

Merced Formation

Late Pliocene non-marine to marine sedimen- ary rocks, tentatively correlated by McNitt (1968a) ith the Merced Formation, are present along the estern flanks of the Mayacmas Mountains near ittle Sulphur Creek. Lithologically, these oderately well consolidated sediments grade up- ard from a massive red conglomerate at the base to gray siltstone containing minor limestone lenses ear the top. Thickness ranges up to 2000 feet and e rocks rest with angular unconformity upon the ranciscan and associated rocks.

Parts of the Merced Formation are unstable and re subject to landslide activity, particularly when ndercut for road or other construction purposes. A ontributing factor to the instability may be that ese rocks rest, in large part, upon the unstable wer or melange unit of the Franciscan assemblage. liding along contacts, adverse dip, and general low trength are also major contributing factors.

Cache Formation

Lying stratigraphically beneath the volcanic ocks in the Clear Lake physiographic area is the ache Formation of Late Pliocene to Pleistocene ge. The well-bedded, poorly consolidated acustrine deposits crop out in serpentine fashion round the edges of the terrace deposits and olcanic rocks in the Big Valley area near elseyville, and to the east, from the vicinity of och Lomond to Lower Lake. Another small out- rop area is present along the east margin of The eysers GRA in Coyote Valley.

The Cache Formation, which consists of fine andstone, siltstone, and blue clay, lies in un- onformable contact upon the Franciscan rocks on e west and upon the rocks of the Great Valley equence and Tertiary formations to the east.

Brice (1953) and Swe and Dickinson (1970) indicate that it is difficult to determine the thickness of the Cache Formation and the configuration of its depositional basins. They postulate late Tertiary-early Quaternary orogeny affecting earlier thrusts and unconformities in the area, synorogenic deposition of the Cache Formation, and volcanism beginnning in the final stages of Cache Formation deposition. This would mean that widely variable thicknesses of Cache Formation rocks may be present beneath the Clear Lake volcanic rocks. Some geologists suggest the possibility of down-dropped fault blocks with deposition of great thicknesses of Cache sediments all lying beneath the volcanic rocks. Published thicknesses range from 300-400 feet within The Geysers GRA, but thicknesses up to 6500 feet are computed by Brice for an area outside the GRA.

Both erosion and landslide activity appear to be problems associated with the sediments of the Cache Formation. Wherever they are elevated and abut older or harder rocks, they tend to both slide and erode, resulting in exposure of the underlying surface.

Sonoma Volcanics

The southern boundary of The Geysers GRA crosses Mount St. Helena at a point near the top of the peak. An area of Pliocene volcanic rocks, approximately 3 miles (5 km) by 4 miles (6.5 km), located mainly on the flanks of the mountain, is included in the GRA.

In the Mayacmas district, the Sonoma Volcanics consist of andesite and rhyolite tuffs and flows and breccias and agglomerates of basalt andesite and rhyolite. The tuff is predominantly andesitic and ranges from fine- to very coarse-grained pyroclastic rocks that grade into breccia. The maximum thickness of the rocks in this district is of the order of 2000 feet (650 m).

Although there are dikes and plugs in the vicinity that probably represent sites from which the volcanic rocks issued, Mount St. Helena itself is built up of a series of folded flows and beds and is not a former major volcanic vent. The fact that the maximum dip of beds in the vicinity does not exceed 20 degrees indicates that orogenic activity was relatively mild in post-Sonoma Volcanics time.

Clear Lake Volcanic Rocks

Volcanism and its products in the Clear Lake area have been studied in considerable detail by Anderson (1936) and by Brice (1953). Most of the information presented here follows the work of Brice.

The Clear Lake volcanic rocks, which cover approximately one-fourth of The Geysers GRA, are present mainly in the northeast corner and bordering on Clear Lake. Volcanism apparently began in early Pleistocene time bringing to an end the deposition of the Cache Formation. Evidence for this is found in the uppermost Cache beds which contain intercalated rhyolite tuffs and olivine basalt flows. The volcanic activity continued into the Holocene as evidenced in part by solfataric activity associated with obsidian at Borax Lake and the freshness of the cinder cone at Roundtop Mountain. This cinder cone and Mt. Konocti, which is a composite volcano, are the only two proven volcanic vents in the area. However, it is probable that some of the other volcanic prominences nearby such as Mt. Hannah, Cobb Mountain, Boggs Mountain, and Seigler Mountain may also represent vents. Much of the lava may.have been extruded from a system of northwest trending fissures with lavas of various composition coming from different fissures.

Flows and beds having a maximum possible collective thickness of 5700 feet have been described by Brice (1953). However, many of these are deposited in separate areas and are not juxtaposed, and the figure may be very high. Included in the series are rhyolite tuff, olivine basalt, andesitic flows of Perini Hill, andesite flows at Boggs Mountain, the Cobb Mountain rhyolite, pyroxene dacite flows northeast of Mt. Hannah, black obsidian deposited over 5 square miles south of Clear Lake, and gray to pink dacite which formed Mt. Konocti. Similar flows form Mt. Hannah and Seigler Mountain. These rocks were laid down upon a surface of considerable topographic relief. Cobb Mountain, for example, is superposed on, and extends some 800 feet above, the Franciscan rocks of the main ridge of the Mayacmas Range. On the other hand the Cache Formation may have acted as a "buffer" by infilling some of the depressions beneath some of the volcanic rocks.

Many of the volcanic rocks are cliff forming. The fresh unweathered appearance of the flows and domes is an indication of their young age and their durable physical properties. However, erosion of the tuffaceous beds may pose a considerable problem wherever they are exposed, either in natural outcrop or in cut slopes. Additionally, two huge slides, one involving andesitic and the other rhyolitic rocks, are present on the southeast flanks of Boggs Mountain and Cobb Mountain, respectively. These slides, one of which involves tuffaceous rocks, are discussed under the "Landslides" heading.

Terrace Deposits

Quaternary terrace deposits within the GRA are concentrated in the Big Valley area, south of Kelseyville, and in the Glenbrook area along Kelsey and Sulphur Creeks. Other very small terraces, mostly too small to delineate on maps, are present along the banks of streams.

The terraces are composed largely of gravels derived from the pre-Tertiary rocks. Most conspicuous are the chert fragments derived from the Franciscan assemblage, but McNitt (1968a) has observed that obsidian pebbles also make a significant contribution to the terrace gravels near the western flanks of Mt. Konocti. No special engineering problems associated with the terrace gravels are anticipated.

Quaternary Alluvium

Most of the extensive bodies of alluvium withi the GRA are found in the Coyote, Collayomi, an Long Valley areas. Sizable deposits of silt, sand and gravel are found along most of the large streams in the area even though major parts of thei courses are narrow and lie along steep-walle canyons and valleys.

Soils in the various parts of the area tend t vary according to the rock types in the nearby sourc areas. Reddish sandy clays, for example, are ofte associated with the volcanic-flow rocks. Bric (1953) observed that, near large serpentine bodies the soil is plastic when wet and dries rapidly wit much shrinkage. In Long Valley during the dr season, he observed extensive networks of crack with some individual cracks up to 6 inches acros and several feet deep. Such expansive clays requir treatment before engineering structures are founde upon them.

GEOLOGIC STRUCTURE

The geologic structure for most of The Geyser GRA is characterized by the northwest trends of th outcrop patterns of the late Mesozoic rocks and o the fault zones that separate them into tilted an folded blocks or plates of strata (figure 2). The are is essentially bisected by a major thrust fault zon called the Soda Creek thrust by Swe and Dickinso (1970). This zone which apparently follows the lin of serpentine outcrops trending northwestward fro Long Valley between Boggs and Cobb Mountains and through a point just southwest of Boggs Lake marks the line of separation between the outcro areas of the Great Valley sequence on the northeas and the Franciscan assemblage on the southwest

Swe and Dickinson (1970) postulated that together with overthrust Eocene and Paleocen strata, the Great Valley sequence forms a thrus complex that rests structurally upon the Francisca assemblage along the Soda Creek thrust, and i overlain unconformably by late Cenozoic strata. A number of subsidiary thrusts that are discordant t the bedding divide the Great Valley sequence an the Franciscan assemblage each into three or mor successive thrust plates or slices.

Emplacement by regional thrust faulting of th Great Valley sequence and lower Tertiary rock above the Franciscan assemblage was probably complete by Oligocene time after which the entire complex, including the thrust faults themselves, wer folded and cut by faults during later Cenozoic deformations. The late Tertiary-early Quaternar orogeny, which was probably the most effective i this folding and faulting process, also brought wit it, in the later stages, the volcanism that produce the Clear Lake lavas.

Folding and erosion have exposed the Sod Creek thrust and underlying Franciscan rocks, alon e Soda Creek anticline, outside the GRA on the ortheast and also in some nearby smaller windows. he windows lie very close to the area border just outh of Lower Lake. The Howard Springs pierce-ent structure, trending southeast from Seigler ountain, may also expose the Soda Creek thrust, ut if so, erosion of the serpentinite breccia body, resent along the thrust at this locality, has not been eep enough to expose the underlying Franciscan ocks. Swe and Dickinson (1970) suggested that igh-angle reverse faults at the margins, the ser-entinite of low density in the central part of the tructure, and the archlike shape indicate that the oward Springs structure may be diapiric.

The Big Canyon syncline, which parallels the oward Springs structure on the southwest, is soclinal in its mid-section; toward the northwest, it s less tightly folded. The north limb of this fold is runcated by the Big Canyon fault along the edge of he Howard Springs structure.

Of the several subsidiary thrusts or other faults nown to have sizable displacements within the reat Valley sequence, most prominent are the ollayomi fault, which may be associated with the oda Creek thrust in the separation of Great Valley nd Franciscan rocks; the Harbin Mountain thrust, hich cuts out 5700 feet (1900 m) of sedimentary trata; and the Childers Peak fault, which borders he Howard Springs structure on the northeast.

The more important fault zones associated with he Franciscan assemblage outcrop area include (1) he complex fault zone along Big Sulphur Creek hich, according to McNitt (1968a), is the con-rolling structure for the steam field and has a throw hat increases to the northwest (figure 3); (2) the Little Sulphur fault and Black Mountain fault zone hat bound the Little Sulphur graben along Little Sulphur Creek; and (3) the Maacama and Chianti fault zones at the southwest margin of The Geysers GRA. Gealey (1951) estimates that the Sonoma volcanic rocks have been downdropped by nearly 2100 feet (700 m) by the combined action along the Maacama and adjacent Chianti fault zones that border the Mayacmas Mountains on the southwest. These facts would tend to agree, at least in part, with the concept expressed by McNitt (1968a) that the Mayacmas Mountains are a large complex horst bounded by faults.

LANDSLIDES

The Franciscan assemblage is in general unstable under natural conditions because of chemical alteration, innumerable faults and shear zones, and because of the development of tectonic breccias or melange units crushed and mixed within the assemblage (see description under "Franciscan Assemblage"). Experience has shown that interference with the delicate natural balance between such factors as natural slope angle, ground water, vegetation, and surface loading can produce disastrous results, particularly with respect to slopes underlain by melange matrix (photos 3 and 4). Roads constructed over melange terrain are subject to constant repair due to undercutting or removal of rock or soil that supports natural slopes, which causes the weak, internally sheared, and slickensided material to fail. Differential settlement across boundaries between matrix material and inclusions in the Franciscan assemblage is a common problem, as is downhill soil and rock creep. Because of its low permeability, introduction of water into the matrix material decreases shear strength, increases weight, and often leads to slope failures. Removal of vegetation destroys the network of roots which bind the weak soil materials together and, more important, destroys the vegetative canopy which retards infiltration. All of these factors also operate in other terranes, but their effect on melange units is more severe.

Most of the natural landslides that occur in the Franciscan assemblage are caused either directly or indirectly by the poor slope stability conditions inherent to the melange.

Two large slides involving the Clear Lake volcanic rocks, one on Cobb Mountain (rhyolite) and one on Boggs Mountain (andesite), have been mentioned above. At Cobb Mountain, tuff crops out only on the southeastern flank in beds several hundred feet thick. Weak layers or lenses in the tuff beds, because of lack of support, have apparently contributed to the breakdown of the overlying harder rocks and are, in part, responsible for the massive slide. The slide is over 2 miles long and consists, at the top, of rhyolitic debris with blocks up to 30 feet in length. Down slope the rhyolitic debris is mixed with progressively increasing amounts of resistant Franciscan rock types typical of the hard inclusions in the underlying melange unit. This suggests that the incompetent materials of the melange, as well as those of some of the tuff beds, have given way and removed support from the overlying and more competent rhyolitic lavas. Conditions associated with the Boggs Mountain slide suggest a similar origin, except that the volcanic rocks are andesitic and the underlying materials are composed of incompetent shales belonging to the Great Valley sequence. These materials are known to be slide prone.

SEISMICITY

Two active faults with known surface evidence for recent right-lateral displacement pass near the area. These are (1) a segment of the Maacama fault zone that trends along The Geysers GRA boundary in Alexander Valley and (2) the Healdsburg fault about 4 miles (6.5 km) to the southwest. Movement on the Healdsburg fault was responsible for the magnitude (M) 5.6 and 5.7 earthquakes that damaged Santa Rosa, 15 miles (25 km) south of the area, in 1969. Both faults show right-lateral

Photo 1. Large inclusions from Franciscan melange unit restin at the base of a slide along B Sulphur Creek.

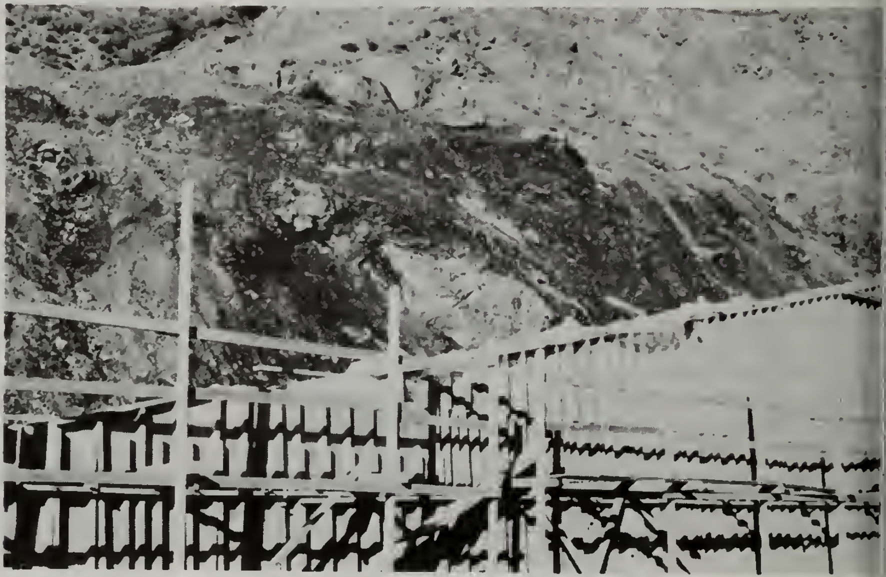


Photo 2. Franciscan melange exposed in cut-slope above a power plant retaining wall.

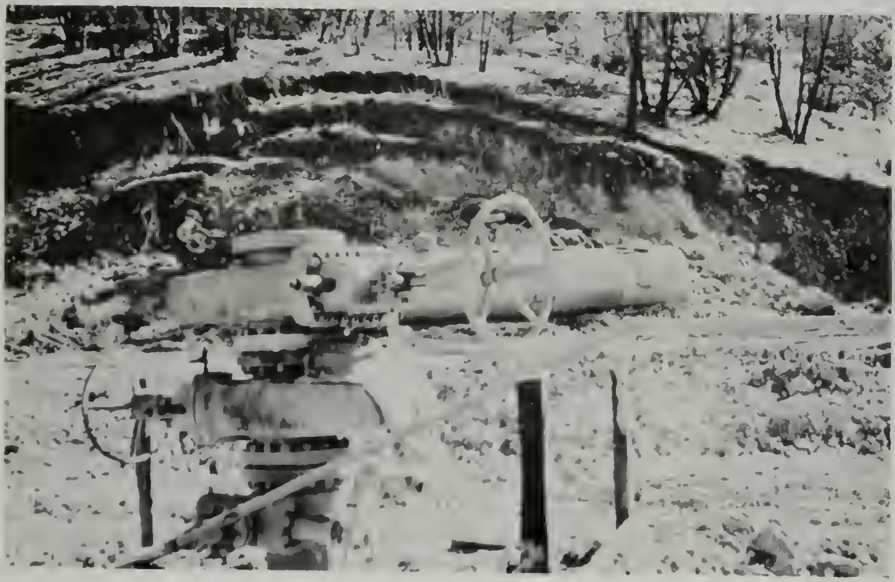


Photo 3. Slide caused by u dercutting of slope at back of dr site.

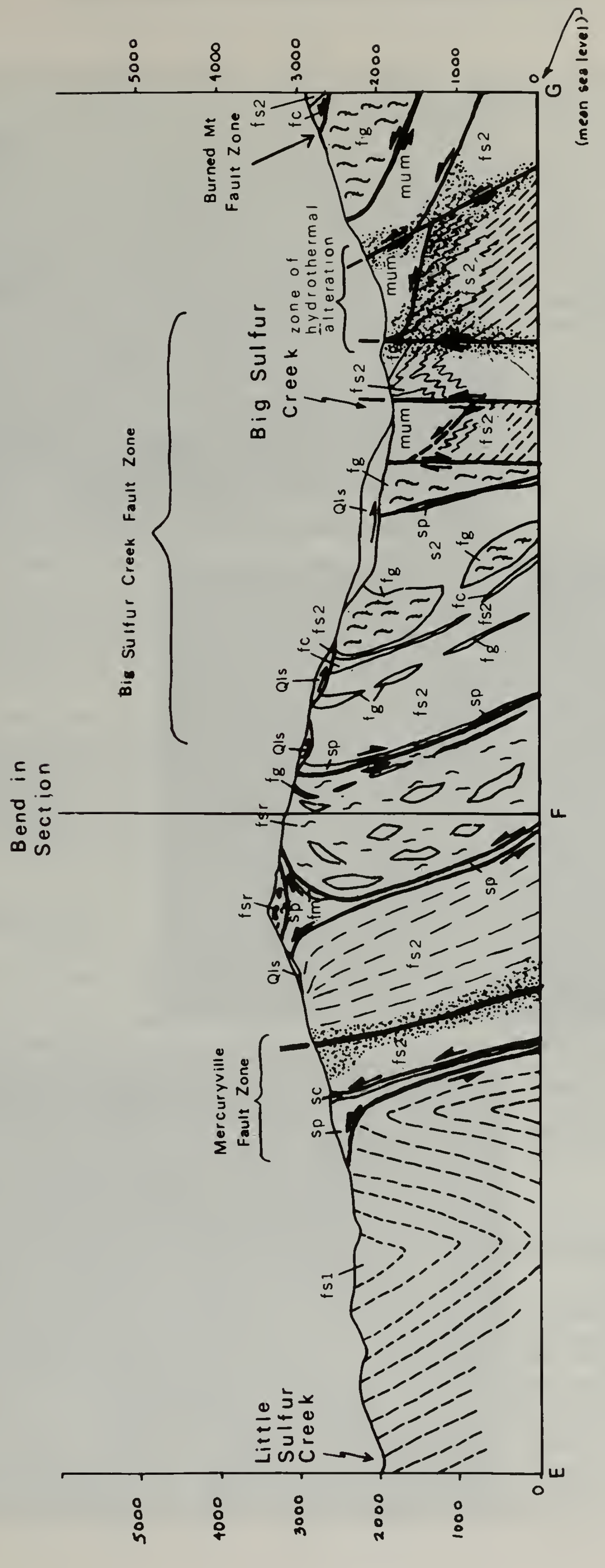


Figure 3. Cross section showing part of the Big Sulfur Creek fault zone. This fault zone is believed by some geologists to be the controlling structure for the steam field (McNitt, 1968a). *From McLaughlin (1974).*

movements and have northwest-southeast trends that parallel those of faults within The Geysers GRA as well as that of the San Andreas fault 29 miles (40 km) to the southwest.

The occurrence of a great earthquake (M >8) along the San Andreas fault could produce significant firm rock accelerations within The Geysers GRA. However, the Healdsburg fault is more important due to its proximity, and it is known to be active. The occurrence of a maximum credible earthquake on this fault may excite an acceleration field varying from slightly greater than 0.2 g to values greater than 0.5 g within The Geysers GRA (Greensfelder, 1974).

Two earthquakes with magnitudes greater than 4 were recorded within The Geysers GRA boundaries between 1934 and 1964. They occurred in 1955, had magnitudes of 4.2 and 4.6, and were centered approximately 4 miles (7 km) southwest of Kelseyville.

A microearthquake study made at The Geysers during a three-week period in 1971 by Hamilton and Muffler (1972) revealed a cluster of epicenters along a zone about 4 km long and 1 km wide passing through the geothermal field along a principal fault zone. Focal depths ranged from near surface to about 4 km, and magnitudes were generally less than 1 on the Richter scale. Fault plane solutions indicated right-lateral strike-slip faulting along a plane trending north-northwest, or subparallel to the regional pattern. This does not correspond with either dip-slip or thrust-fault patterns suggested for the area but probably represents current deformation conditions within the region as influenced by the San Andreas fault system.

Microearthquakes are common in undeveloped geothermal areas. Furthermore, Hamilton and Muffler (1972) observed that geothermal production in other geothermal areas in the world did not increase the number of microearthquakes. This suggests that microearthquakes are not caused by steam extraction but are inherent within the same geologic environs that create the geothermal source. It was further suggested that clear evidence would be obtained by monitoring microearthquakes in geothermal areas both before and after steam extraction operations are begun for power production. A proposal to implement a monitoring program of this type is included in a later section of this report.

MINERAL RESOURCES

The Geysers GRA includes known quicksilver deposits. The Mayacmas quicksilver districts are largely within the southern part of the GRA and old quicksilver mines and facilities (photo 5), are scattered throughout the entire area. More than 35,070 flasks of mercury (76 pounds each) were produced in the Mayacmas district through World War II. Production in recent years, however, has been minor with only a brief flurry of activity during the period of high mercury prices in the middle to late 1960s.

ENGINEERING GEOLOGY

The development activities which may creat hazardous conditions if the geologic environment i not considered are:

1. Road construction.
2. Exploration and development drilling.
3. Slurry handling during drilling.
4. Disposal of slurry and other wastes, liquid and solid.
5. Establishing sites for power-generation facilities and othe permanent structures.
6. Piping steam from well-head to power-generation units.
7. Disposal of condensate from the generators.
8. Establishing power-transmission structures, includin towers, and cleared routes.

The main engineering geology concerns that ar associated with these geothermal energy development activities include:

1. Stability of roads, drillsites, and foundations for structures pipelines, and towers.
2. Safety and permanence of underground systems—mainly the wells that tap the steam sources—and well-head apparatus.
3. Control of leakage or overflow of slurry and noxious liqui wastes involved in drilling operations.
4. Prevention of disruptive changes in ground water systems both hot spring and ordinary ground water springs an seeps.

The geologic processes that are important i resolving engineering geology problems are erosion landslides (including water- and earthquake-relate landslides), liquid waste disposal, compaction, expansive clays, subsidence, seismic shaking, an fault rupture. All of these processes must be considered during planning, building, and maintenanc

Landslides

It is possible to locate structures or other improvements on potential landslide terrain wit satisfactory results; however, this can be accomplished only by considering all of the geologi environs and processes affecting each individual sit (photos 6 and 7). A building or well site that is to b located on melange terrain on a very large firm inclusion or on an extensive flat surface or valley floo might prove satisfactory, while a site located on comparatively gentle slope might prove a complet failure. An engineering geology assessment of eac construction or well site is mandatory to mitigat the potential for landsliding (photos 8 and 9).

Erosion Control

Due to the steep terrain and characteristics the soils in The Geysers GRA, accelerated erosio is likely for on-site and downstream areas if improper grading and drainage control activities ar allowed (photos 10-15). Also, severe downstrea sedimentation will result from erosion that occu during landsliding. Erosion control measur should provide (1) the protection of exposed soil cut, fill, and other graded areas or roads ar geothermal well sites and (2) the control of drainag

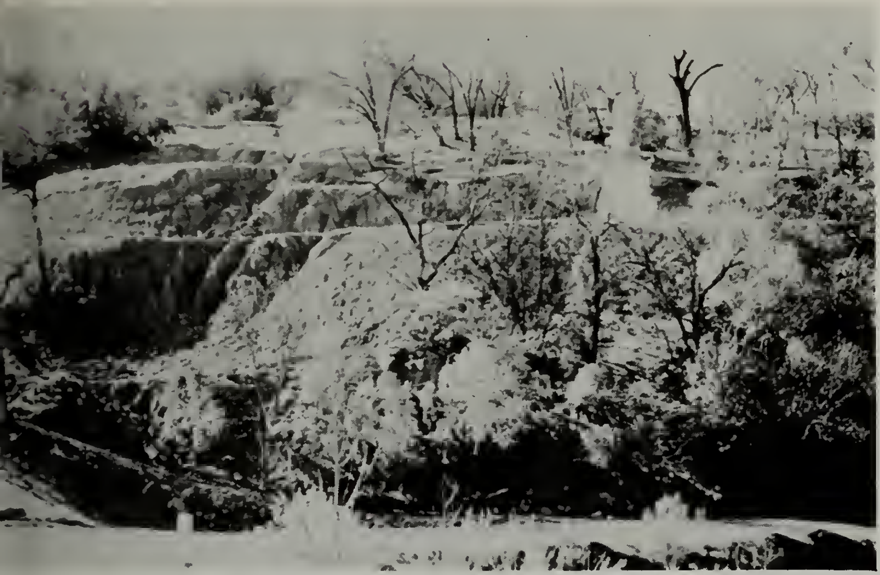


Photo 4. Erosion and sliding has occurred on benches cut for geothermal well drilling operations.

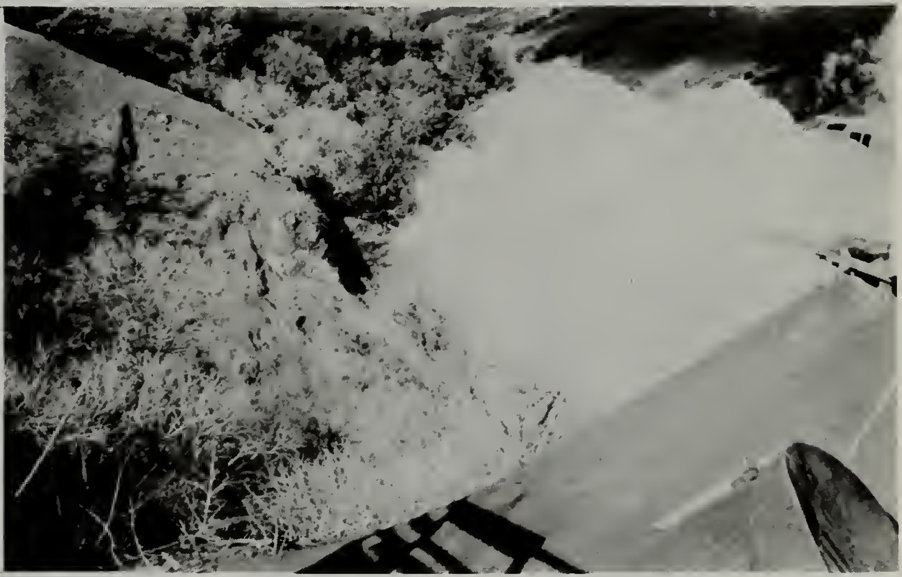


Photo 5. Slide on a hillside above a geothermal well site (well head is behind steam cloud). View from dump of old mercury mining operation.

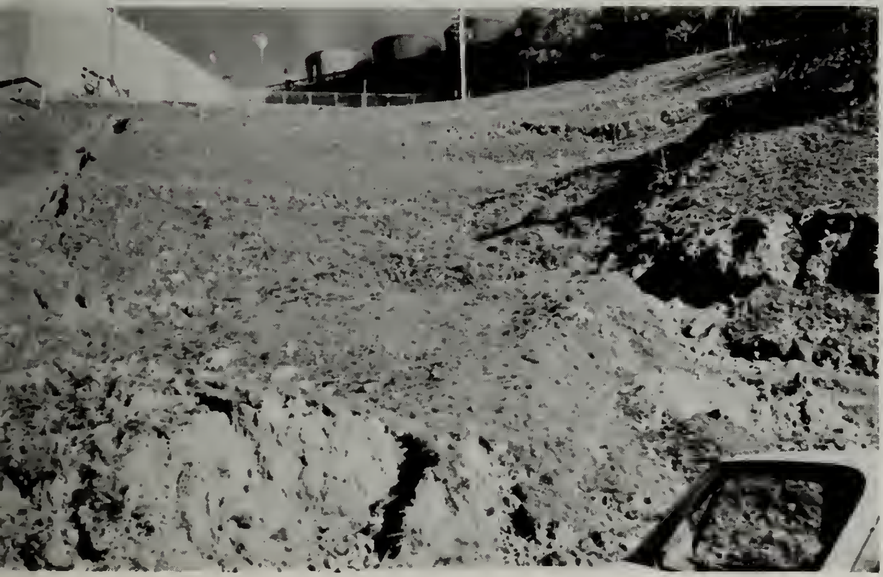


Photo 6. An example of landslide encroachment on a power plant site.

Photo 7. Another power plant with a situation similar to that illustrated in photo 6.

Photo 8. Slumping and erosion at well site associated with un-compacted, nonengineered fill.

Photo 9. Drill sump contents were mixed with the nonengineered fill material to build road, with slumping and erosion resulting from instability of materials.

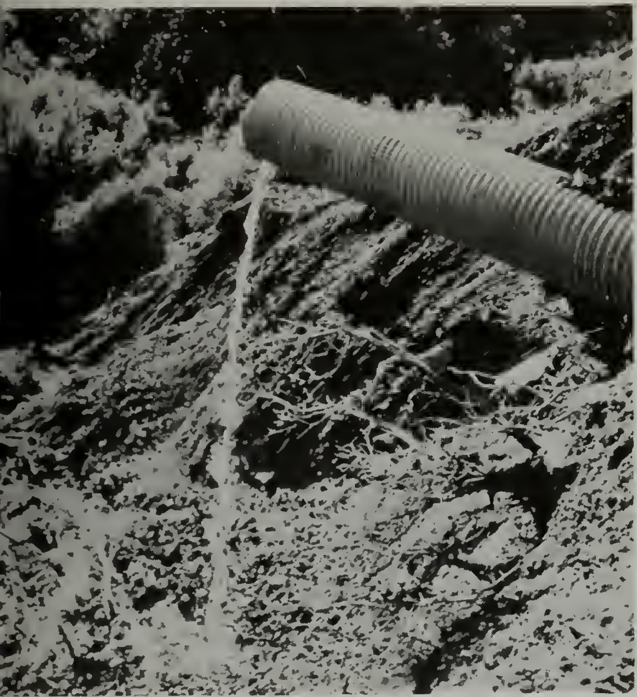


Photo 10. Inadequate drainage has been a major factor causing slumping.

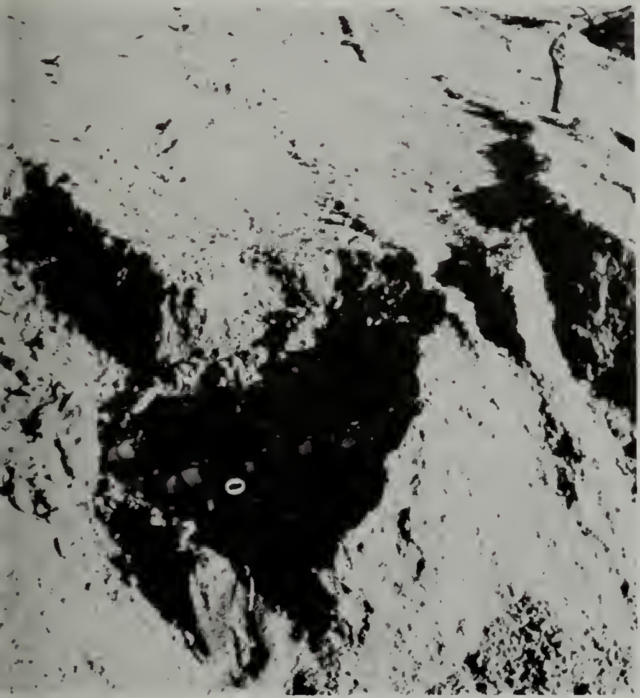


Photo 11. Slumping and erosion have occurred in nonengineered fill material mixed with drill sump contents near a well site.

Photo 12. Hay used as a filter for rainfall to control erosion on slopes at this drill site.

Photo 13. Hay used for a mulch cover over this planted slope near a power plant. The drainage ditch has been coated with gunite to prevent erosion at sides and bottom of trench.

from rainfall and springs. These measures should be required wherever construction activity alters the landscape, drainages, and runoff.

Liquid Waste Disposal

Under current practice, effluent from power plant operations is pumped to the well head of an injection well and injected by gravity (under vacuum conditions). It is anticipated that this practice will continue. Other waste materials, including drill sump (mud pit) contents are and should be conveyed to an official disposal site of the proper class for disposition (photo 16).

Expansive Soils

Highly expansive soils are present in many parts of the GRA and, while it may be possible to construct engineered structures on sites where these soils are present, remedial methods will be required to obtain a suitable and stable foundation. Remedial methods may require removal of expansive soil and backfilling with stable material (soil or cement).

Ground-Water Contamination

Contamination of fresh ground-water sources is an ever-present possibility in any project involving major construction and drilling operations. Contamination can occur from subsurface introduction of contaminated fluids into fresh water aquifers through poorly cased wells, through percolation, or from surface mixing at springs and streams.

Contamination of surface and ground waters has occurred at times within the area as a result of leaking drill sumps and spills of deleterious fluids on the ground surface, on banks, and in drainage ditches. In some instances fills have been placed over existing springs (photo 14), resulting in water contamination, erosion, and failure of fill. These practices should be discontinued, and adequate inspection should be provided to assure continued protection of naturally occurring waters.

Seismic and Subsidence Measures

Subsidence is not presently known to occur in the GRA, and no evidence has been presented to indicate that any adverse seismic impacts from geothermal production are present. However, as the tectonic stress field in the area is imperfectly understood, and as fluid injection has been correlated with small earthquake occurrence in high tectonic shear and stress areas elsewhere, appropriate monitoring should be established as outlined under "Procedures for Monitoring Earthquake Activity". If a problem is indicated, appropriate action, such as changes of injection techniques or changes in steam production, can be initiated to alleviate the problem.

RECOMMENDED MITIGATING MEASURES

The following procedures should be required by the permit-issuing authority:

1. PROCEDURES REGARDING LANDSLIDES
   a. Except as provided under b. below, where the following geologic conditions exist (photos 17 and 18), no construction of roads or geothermal facilities should be allowed unless safe and stable mitigating procedures can be proven:
      (1) On active landslides, such as those indicated by recent scarps, tilting of trees, or hummocky ground.
      (2) On slopes which are subject to landslide activity due to construction activity or geothermal facilities.
      (3) On slopes which are subject to landslide activity due to natural geologic conditions or on incipient or ancient landslides which have a high probability of being activated by earthquakes during the life of the project.
   b. Where the following geologic conditions exist, construction of roads and geothermal facilities should be permitted as "conditionally allowed" (meaning that measuring devices should be placed at regular intervals to a depth exceeding that of the potential failure plane and strictly monitored for landslide movement):
      (1) On incipient slides or slopes subject to landslide activity where the construction of roads, well sites, and building sites could cause alteration of the landscape and drainage facilities and thereby decrease slope stability.
      (2) On older inactive landslides with a history of sliding, which have not moved recently, but which have a potential for failure.
   c. Construction of roads and geothermal facilities could be permitted on all other areas as deemed stable or correctable by good engineering geology and engineering practices.

2. PROCEDURES REGARDING EROSION CONTROL
   a. Graded surfaces should be protected against erosion as follows:
      (1) Cut-and-fill-slopes should be landscaped using mulches and irrigation if necessary; the established vegetation should provide effective and permanent erosion control equal to or exceeding that of the original naturally vegetated conditions.
      (2) The fill shall be compacted to 90% relative density (see Uniform Building Code [UBC], 1973, or latest edition).
      (3) All geothermal well sites (level sites) should be paved or treated so that the surfaces are nonerodible and shall be provided with adequate nonerosive drainage devices.
      (4) All runoff from rainfall and springs should be collected in engineered drainage devices and diverted to prevent concentrated runoff along the surfaces of cuts, fills, roads, and geothermal well sites.

Photo 14. Drill site constructed over a spring; ensuing erosion was caused by inadequate drainage.

hoto 15. A road at the edge of a rill site has slumped and eroded ue to inadequate drainage.

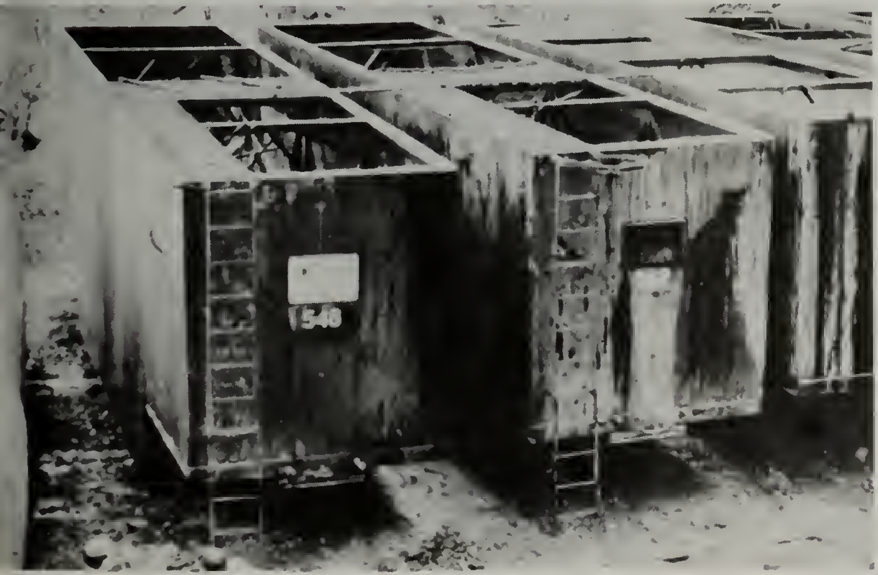


Photo 16. "Baker tanks" were used here to replace cut-and-fill type sumps.

Photo 17. Well sited on a hydrothermally altered landslide area.

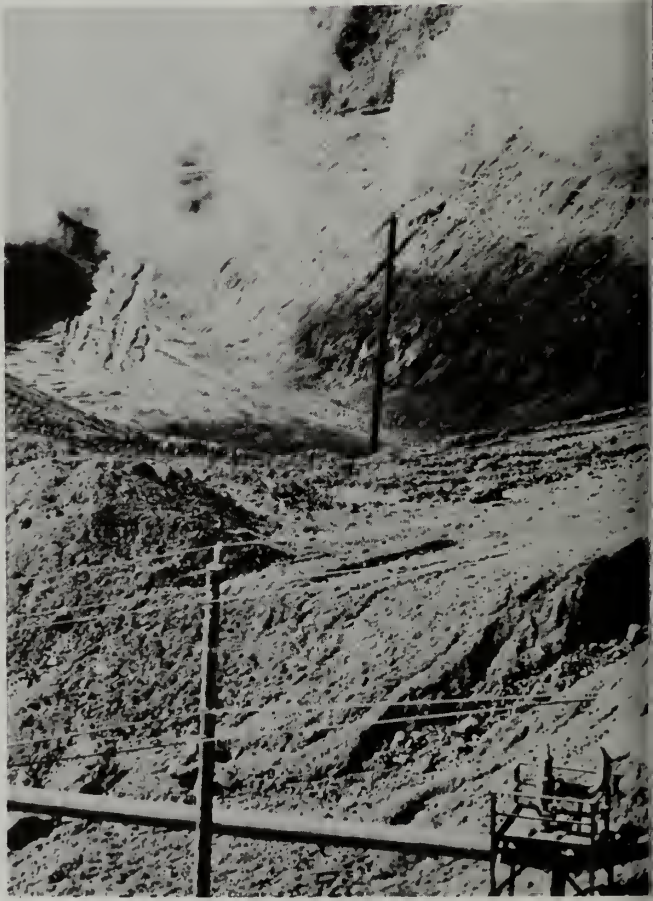


Photo 18. At this well site, 70± feet of material were removed to replace damaged casing.

(5) Temporary drainage control measures should be installed before and/or during grading to prevent erosion before the final grading is completed; provision shall be made for a qualified Soil Engineer or Engineering Geologist to make certain that the site has been properly cleaned, graded, and protected from erosion upon drilling completion.

b. Drainageways should be protected against erosion as follows:

(1) Mechanical devices, such as sediment debris basins or drop structures, should be installed to reduce the rate of runoff when the natural drainageways are susceptible to erosion from accelerated runoff.

(2) Protective devices, such as riprap, or other energy-dissipating structures should be placed at all points of concentrated discharge.

c. Erosion along landslides caused by construction activity, extraction of geothermal energy, natural causes, or by the leakage of steam and saturation of unstable slopes and which impinge upon roadways, drainageways, or geothermal facilities should be mitigated in the following manner:

(1) The landslide should be stabilized against further movement, and the landslide surface should be graded and landscaped.

(2) The spoil material from the landslide should be placed at a location and in a manner that erosion will not occur.

(3) The surface of the landslide, including the scarps, should be landscaped for effective erosion control.

3. PROCEDURES REGARDING LIQUID WASTE DISPOSAL

The permeability and the stability of the geologic units shall be considered so that toxic drilling fluids and/or other deleterious substances will not escape downslope from an operating site and/or into a stream channel.

4. PROCEDURES REGARDING EXPANSIVE SOIL

The potential problems of expansive soils shall be identified and mitigating procedures proposed by the Soil Engineer so that the proposed development will not cause detrimental environmental impact.

5. PROCEDURES REGARDING GROUND-WATER CONTAMINATION

Ground-water resources should be identified at all sites of proposed development, and adequate measures should be taken to prevent ground-water contamination.

6. PROCEDURES REGARDING SOIL ENGINEERING AND ENGINEERING GEOLOGY INVESTIGATIONS

Engineering Geology and Soil Engineering reports shall be required for all roads, pipe lines, drill sites, construction sites, and other sites for engineered facilities. It is recommended that CDMG Notes 37, 43, 44, and 46 be used as guidelines for the preparation of the Engineering Geology reports.(see Appendix 2)

The responsibility for identifying the soil and the geologic problems and the design of mitigating measures to prevent environmental damages shall be provided by the soil engineer and the engineering geologist.

The owner or operator of the geothermal project shall provide assurances that the recommendations of the soil engineer and the engineering geologist are to be fully implemented.

The California Division of Mines and Geology recommends that the checklist in figure 4 be used by reviewers of environmental impact reports for geologic hazards at geothermal well facilities.

The same checklist should be used also for temporary roads, trails, and drill sites that may be built as part of the exploratory activity.

7. PROCEDURES FOR MONITORING EARTHQUAKE ACTIVITY

Tectonic activity, seismic or aseismic, must be considered when planning a geothermal exploration or exploitation program. Evidence of geologically recent displacements and high levels of tectonic microseismicity indicate that precautions must be exercised during and after exploration programs. Geothermal related microseismicity should be monitored continuously before, during, and after drilling of the geothermal site.

Two types of seismicity are identified for consideration during the exploration and exploitation of a geothermal area; these are tectonic and geothermal seismicity. Tectonic seismicity would be those earthquakes associated with the deformation of the Earth's crust and geothermal seismicity would be shocks associated with geothermal processes whether or not the processes are a naturally occurring or induced phenomenon attributable to disturbing the geologic environment.

Tectonic activity has in a few locations destroyed petroleum production facilities, and so consideration must be given to minimizing potential damage to geothermal facilities resulting from tectonic displacements, earthquake-induced shaking and landslides. The seismic history of a geothermal area should be reviewed and analyzed; if, during exploration programs, evidence is found indicating geologically recent fault movements or a high incidence of microseismicity, the general area should be considered tectonically active and maximum precautions should be exercised during all phases of geothermal development.

a. Temporary seismic instrumentation.

Geothermal seismicity could be monitored prior to any development of a geothermal site regardless of the nature of the well (exploratory or development). A minimum of four months of continuous seismic recording at some selected typical well sites could be considered. When drilling has begun seismic observations could be continued but at some distance, perhaps several kilometers, from the drill

REVIEW OF GEOLOGIC HAZARDS IN THE ENVIRONMENTAL IMPACT REPORTS FOR GEOTHERMAL WELL LOCATIONS

Project________________ County__________ File No.__________ Date__________

CRITERIA FOR DETERMINING EVIDENCE OF COMPLIANCE WITH CHAPTER 70 UBC (1973)	*DOES THE DEVELOPMENT SITE HAVE THESE CONDITIONS?*			*IS THE CONDITION ADEQUATELY DISCUSSED IN ATTACHED REPORTS*	
I VALID USE OF CHAPTER 70 UBC REQUIRES	*Yes*	*No*	*Not indicated*	*Yes*	*No*
1. Soils Engineering Reports When:					
a. Depth (or height) of cut or fill is 3 feet or greater	☐	☐	☐	☐	☐
b. Fill is to support structural footings	☐	☐	☐	☐	☐
c. Engineered cut or fill is required (grading in excess of 5000 cubic yards is necessary)	☐	☐	☐	☐	☐
d. Soils are or may be subject to shrink-swell	☐	☐	☐	☐	☐
e. Area is subject to erosion and sedimentation (exposed erodible soil, alteration of runoff, unprotected drainageways, increased impervious surfaces)	☐	☐	☐	☐	☐
2. Engineering Geology Reports When:					
a. Finished cut slope faces are more than 10 feet high	☐	☐	☐	☐	☐
b. Existing slope is steeper than 5 horizontal to 1 vertical	☐	☐	☐	☐	☐
c. Existing cut slope is more than 10 feet high	☐	☐	☐	☐	☐
d. Existing stream bank cliffs, etc., are in excess of 10 feet	☐	☐	☐	☐	☐
e. Seismic hazards exist or are suspected (fault movement, liquefaction, landslides, ground rupture, differential compaction, ground shaking, extraction of geothermal energy, injection of geothermal waste)	☐	☐	☐	☐	☐
f. Ground-water hazards exist or are suspected	☐	☐	☐	☐	☐
g. Area is underlain by landslides or soil creep or by rock material susceptible to landslide or creep	☐	☐	☐	☐	☐
h. Alluvial material, slope wash, or rock materials exist that are subject to settlement, subsidence, or hydrocompaction	☐	☐	☐	☐	☐
i. Area is subject to erosion and sedimentation (exposed erodible soil, alteration of runoff, unprotected drainageways, increased impervious surfaces)	☐	☐	☐	☐	☐
j. Area is subject to volcanic activity (lava flow, ash fall)	☐	☐	☐	☐	☐
II REPORTS SHOULD ALSO BE REQUIRED WHEN:					
1. Area is subject to land subsidence (extraction of geothermal energy)	☐	☐	☐	☐	☐
2. Mineral resources would be lost (loss of access, deposits covered by changed land-use conditions, zoning restrictions)	☐	☐	☐	☐	☐
3. Waste disposal problems exist (waste from grading, waste from drilling operations)	☐	☐	☐	☐	☐

NOTE: Attach grading plan, general location map, soils engineering report, and engineering geology report.

Developer/owner/operator ____________________

Person to contact ________________ Title __________

Company name ____________________

Address ____________________

Telephone number ____________________

Figure 4. Suggested checklist for review of environmental impact reports for geologic hazards at geothermal well facilities. A suggested signature block is in Appendix 5.

site. An observed increase or decrease in the seismicity could be interpreted as an anomalous condition indicating the need of additional geophysical investigations. Upon completion of drilling operations, seismic monitoring could again be instituted at the initial observation site (if possible). The collection of geothermal seismicity data could continue for at least a period of four months after drilling has ceased. If seismicity is recorded efforts should be made to correlate the seismicity with the various pertinent well parameters, such as temperature, pressure, and production rates. These parameters could be recorded continuously even during the final stage of seismic monitoring.

Seismic monitoring of geothermal areas could be accomplished with a single component seismograph system capable of a magnification of at least 10^6 in the frequency range of 10-30 hz (cycles); recordings should be on a time base permitting a reading accuracy of 0.2 second. Because single station observations are to be made, no elaborate timing system is required. Single observational sites within a proposed geothermal development area should not be considered as adequate; the effect of numerous wells upon the geothermal seismicity is unknown and anomalous conditions which may be unique to wells should be identified.

b. *Permanent seismic instrumentation.* The instrumentation described under Temporary Seismic Instrumentation is applicable to the initial development of a particular geothermal field. After an area has been developed as a geothermal resource area, monitoring of the seismic field should be continued. Similar equipment could be installed near the producing field to monitor the effect of earthquakes and ground shaking on the power facilities. A desirable modification to the recorder unit would be the ability to record a standard radio time signal such as WWV. On the basis of the fact that the maximum distance from the producing well to the power station is about 2000 feet, it is estimated that one permanent seismic station may be needed per square mile of geothermal development.

REFERENCES

nderson, C. A., 1936, Volcanic history of the Clear Lake area, California: Geological Society of America Bulletin, v. 47, p. 629-664.

ailey, E. H., 1946, Quicksilver deposits of the western Mayacmas district, Sonoma County, California: California Journal of Mines and Geology, v. 42, no. 3, p. 199-230.

ailey, E. H., Irwin, W. P., and Jones, D. L., 1964, Franciscan and related rocks and their significance in the geology of western California: California Division of Mines and Geology Bulletin 183, 177 p.

ake, M. C., Jr., Smith, J. T., Wentworth, C. M., and Wright, R. H., 1971, Preliminary geologic map of western Sonoma County and northernmost Marin County, California: U.S. Geological Survey-Department of Housing and Urban Development Basic Data Contribution 12.

ice, J. C., 1953, Geology of the Lower Lake quadrangle, California: California Division of Mines Bulletin 166, 72 p.

hapman, R. H., 1975, Geophysical study of the Clear Lake region, California: California Division of Mines and Geology Special Report 116, 23 p.

hapman, R. H., and Bishop, C. C., 1975, Bouguer gravity map of California, Santa Rosa sheet: California Division of Mines and Geology, scale 1:250,000.

arrison, L. W., 1972, Geothermal steam in The Geysers in the Clear Lake region, California: Geological Society of America Bulletin, v. 83, no. 5, p. 1449-1468.

ealey, W. K., 1951, Geology of the Healdsburg quadrangle, California: California Division of Mines Bulletin 161, 75 p.

reensfelder, R. W., 1974, Maximum credible rock acceleration from earthquakes in California: California Division of Mines and Geology Map Sheet 23, scale 1:2,500,000.

amilton, R. M., and Muffler, L. J. P., 1972, Microearthquakes at The Geysers geothermal area, California: Journal of Geophysical Research, v. 72, no. 11, p. 2081-2086.

Hodges, C. A., 1966, Geomorphic history of Clear Lake, California: Unpublished Ph.D. thesis, Stanford University, Stanford, California, 179 p.

Hsu, K. J., 1969, Preliminary report and geologic guide to Franciscan melanges, Morro Bay-San Simeon Area, California: California Division of Mines and Geology Special Publication 35, 46 p.

Irwin, W. P., 1960, Geologic reconnaissance of the northern Coast Ranges and Klamath Mountains, California, with a summary of mineral resources: California Division of Mines Bulletin 179, 80 p.

Jennings, C. W., and Strand, R. G., 1960, Geologic map of California, Olaf P. Jenkins edition, Ukiah sheet: California Division of Mines and Geology, scale 1:250,000.

Koenig, J. B., 1963, Geologic map of California, Olaf P. Jenkins edition, Santa Rosa sheet: California Division of Mines and Geology, scale 1:250,000.

Koenig, J. B., 1969, The Geysers geothermal field, 1969: California Division of Mines and Geology, Mineral Information Service, v. 22, no. 8, p. 123-128.

McLaughlin, R. J., 1974, Preliminary geologic map of The Geysers Steam Field and vicinity, Sonoma County, California: U.S. Geological Survey open-file map 74-238.

McNitt, J. R., 1968a, Geology of the Kelseyville quadrangle, Sonoma, Lake, and Mendocino Counties, California: California Division of Mines and Geology Map Sheet 9, scale 1:62,500.

McNitt, J. R., 1968b, Geology of the Lakeport quadrangle, Lake County, California: California Division of Mines and Geology Map Sheet 10, scale 1:62,500.

Swe, Win, and Dickinson, W. R., 1970, Sedimentation and thrusting of Late Mesozoic rocks in the Coast Ranges near Clear Lake, California: Geological Society of America, v. 81, no. 1, p. 165-188.

Yates, R. G., and Hilpert, L. S., 1946, Quicksilver deposits of the eastern Mayacmas district, Lake and Napa Counties, California: California Journal of Mines and Geology, v. 42, no. 3, p. 231-286.

APPENDIX 1

(in pocket)

PRELIMINARY GEOLOGIC MAP OF THE GEYSERS STEAM FIELD AND VICINITY, SONOMA COUNTY, CALIFORNIA

By Robert J. McLaughlin

Note: Appendix 1 is U. S. Geological Survey Open File Map 74-238 reprinted, with the author's permission, with a colored overlay showing the locations of 168 geothermal wells and geothermal power plants 1 through 12. Locations of the wells and the power plants were obtained from maps supplied by Union Oil Co. and the California Division of Oil and Gas, and from the *Munger Oilogram.*

The geothermal well locations were plotted on the geologic map during investigations after the blowout of geothermal well "GDC" 65-28 (Union Oil Co.). Of the 168 wells plotted in the area mapped by McLaughlin, 91 are on areas shown as landslides.

APPENDIX 2

G NOTES **NUMBER 37**

GUIDELINES TO GEOLOGIC/SEISMIC REPORTS

The following guidelines are taken from "Geology nd earthquake hazards: Planners guide to the seismic fety element" prepared by Grading Codes Advisory oard and Building Code Committee of the Southern alifornia Section, Association of Engineering Geologists, ly, 1973. They are reprinted here courtesy of the ssociation of Engineering Geologists.

Introduction

This is a suggested guide or format for the seismic ection of engineering geologic reports. These reports ay be prepared for projects ranging in size from a single t to a master plan for large acreage, in scope from a ngle family residence to large engineered structures, nd from sites located on an active fault to sites a sub- antial distance from the nearest known active fault. ecause of this wide variation, the order, format, and ope should be flexible and tailored to the seismic and eologic conditions, and intended land use. The following ggested format is intended to be relatively complete, nd not all items would be applicable to small projects or w risk sites. In addition, some items would be covered separate reports by soil engineers, seismologists, or ructural engineers.

. *The Investigation*

A. *Regional Review*

A review of the seismic or earthquake history of the region should establish the relationship of the site to known faults and epicenters. This would be based primarily on review of existing maps and technical literature and would include:

1. Major earthquakes during historic time and epicenter locations and magnitudes, near the site.
2. Location of any major or regional fault traces affecting the site being investigated, and a discussion of the tectonic mechanics and other relationships of significance to the proposed construction.

B. *Site Investigation*

A review of the geologic conditions at or near the site that might indicate recent fault or seismic activity. The degree of detail of the study should be compatible with the type of development and geologic complexity. The investigation should include the following:

1. Location and chronology of local faults and the amount and type of displacement estimated from historic records and stratigraphic relationships. Features normally related to activity such as sag ponds, alignment of springs, offset bedding, disrupted drainage systems, offset ridges, faceted spurs, dissected alluvial fans, scarps, alignment of landslides, and vegetation patterns, to name a few, should be shown on the geologic map and discussed in the report.
2. Locations and chronology of other earthquake induced features caused by lurching, settlement, liquefaction, etc. Evidence of these features should be accompanied with the following:
    - a. Map showing location relative to proposed construction.
    - b. Description of the features as to length, width and depth of disturbed zone.
    - c. Estimation of the amount of disturbance relative to bedrock and surficial materials.
3. Distribution, depth, thickness and nature of the various unconsolidated earth materials, including ground water, which may affect the seismic response and damage potential at the site should be adequately described.

C. *Methods of Site Investigation*

1. Surface investigation
    - a. Geologic mapping.
    - b. Study of aerial photographs.
    - c. Review of local ground water data such as water level fluctuation, ground water barriers or anomalies indicating possible faults.
2. Subsurface investigation
    - a. Trenching across any known active faults and suspicious zones to determine location and recency of movement, width of disturbance, physical condition of fault zone materials, type of displacement, and geometry.

(over)

APPENDIX 2 (continued)

b. Exploratory borings to determine depth of unconsolidated materials and ground water, and to verify fault-plane geometry. In conjunction with the soil engineering studies, obtain samples of soil and bedrock material for laboratory testing.

c. Geophysical surveys which may indicate types of materials and their physical properties, ground water conditions, and fault displacements.

III. *Conclusions and Recommendations*

At the completion of the data accumulating phase of the study, all of the pertinent information is utilized in forming conclusions of potential hazard relative to the intended land use or development. Many of these conclusions will be revealed in conjunction with the soil engineering study.

A. *Surface Rupture Along Faults*

1. Age, type of surface displacement, and amount of reasonable anticipated future displacements of any faults within or immediately adjacent to the site.
2. Definition of any areas of high risk.
3. Recommended building restrictions or use-limitations within any designated high risk area.

B. *Secondary Ground Effects*

1. Estimated magnitude and distance of all relevant earthquakes.
2. Lurching and shallow ground rupture.
3. Liquefaction of sediments and soils.
4. Settlement of soils.
5. Potential for earthquake induced landslide.

IV. *Presentation of Data*

Visual aids are desirable in depicting the data and may include:

A. *General data*

1. Geologic map of regional and/or loca faults.
2. Map(s) of earthquake epicenters.
3. Fault strain and/or creep map.

B. *Local or site data*

1. Geologic map.
2. Geologic cross-sections illustratin displacement and/or rupture.
3. Local fault pattern and mechanics relative to existing and proposed ground surface.
4. Geophysical survey data.
5. Logs of exploratory trenches and borings.

V. *Other Essential Data*

A. *Sources of data*

1. Reference material listed in bibliography.
2. Maps and other source data referenced.
3. Compiled data, maps, plates included o referenced.

B. *Vital support data*

1. Maximum credible earthquake.
2. Maximum probable earthquake.
3. Maximum expected bedrock acceleration.

C. *Signature and license number of geologis registered in California*

JES 8/

APPENDIX 2 (continued)

NOTE **NUMBER 43**

RECOMMENDED GUIDELINES FOR DETERMINING THE MAXIMUM CREDIBLE AND THE MAXIMUM PROBABLE EARTHQUAKES

The following guidelines were suggested by the eotechnical Subcommittee of the State Building Safety oard on 3 February 1975 to assist those involved in the eparation of geologic/seismic reports as required by gulations of the California Administrative Code, Title 7, Chapter 8, Safety of Construction of Hospitals. DMG is currently using these guidelines when reviewing ologic/seismic reports.

aximum credible earthquake

The maximum credible earthquake is the maximum rthquake that appears capable of occurring under the esently known tectonic framework. It is a rational and lievable event that is in accord with all known geologic d seismologic facts. In determining the maximum edible earthquake, little regard is given to its probability occurrence, except that its likelihood of occurring is eat enough to be of concern. It is conceivable that the aximum credible earthquake might be approached more equently in one geologic environment than in another.

The following should be considered when deriving e maximum credible earthquake:

) The seismic history of the vicinity and the geologic province;
) the length of the significant fault or faults which can affect the site within a radius of 100 kilometers; (See CDMG Preliminary Report 13);
(c) the type(s) of faults involved;
(d) the tectonic and/or structural history;
(e) the tectonic and/or structural pattern or regional setting (geologic framework);
(f) the time factor shall not be a parameter.

Maximum probable earthquake (functional-basis earthquake)

The maximum probable earthquake is the maximum earthquake that is likely to occur during a 100-year interval. It is to be regarded as a probable occurrence, not as an assured event that will occur at a specific time.

The following should be considered when deriving the "functional-basis earthquake":

(a) The regional seismicity, considering the known past seismic activity;
(b) the fault or faults within a 100 kilometer radius that may be active within the next 100 years;
(c) the types of faults considered;
(d) the seismic recurrence factor for the area and faults (when known) within the 100 kilometer radius;
(e) the mathematic probability or statistical analysis of seismic activity associated with the faults within the 100 kilometer radius (the recurrence information should be plotted graphically);
(f) the postulated magnitude shall not be lower than the maximum that has occurred within historic time.

PYA, JES, RWS 2/75

APPENDIX 2 (continued)

CDMG NOTE **NUMBER**

RECOMMENDED GUIDELINES FOR PREPARING ENGINEERING GEOLOGIC REPORTS

The following guidelines are required for engineering geologic reports submitted to the Department of Public Works, County of Ventura. This information was originally printed in *California Geology*, November 1974. These guidelines are an example of "State-of-the-Art", and all the elements should be considered during the preparation and review of geologic reports. Item V was provided by the Southern California Section, Association of Engineering Geologists; the State Building Safety Board; and the California Division of Mines and Geology.

I. GEOLOGIC MAPPING

A. Each report must be a product of independent geologic mapping of the subject area at an appropriate scale and in sufficient detail to yield a maximum return of pertinent data. In connection with this objective, it may be necessary for the geologist to extend his mapping into adjacent areas.

B. All mapping should be done on a base with satisfactory horizontal and vertical control—in general a detailed topographic map. The nature and source of the base map should be specifically indicated. For sub-divisions, the base map should be the same as that to be used for the tentative map or grading plan.

C. Mapping by the geologist should reflect careful attention to the lithology, structural elements, and three-dimensional distribution of the earth materials exposed or inferred within the area. In most hillside areas these materials will include both bedrock and surficial deposits. A clear distinction should be made between observed and inferred features and relationships.

D. A detailed large-scale map normally will be required for a report on a tract, as well as for a report on a smaller area in which the geologic relationships are not simple.

E. Where three-dimensional relationships are significant but cannot be described satisfactorily in words alone, the report should be accompanied by one or more appropriately positioned structure sections.

F. The locations of test holes and other specific sources of subsurface information should be indicated in the text of the report or, better, on the map and any sections that are submitted with the report.

II. GENERAL INFORMATION

Each report should include definite statements concerning the following matters:

A. Location and size of subject area, and its general setting with respect to major geographic and geologic features.

B. Who did the geologic mapping upon which the report is based, and when the mapping was done.

C. Any other kinds of investigations made by the geologist and, where pertinent, reasons for doing such work.

D. Topography and drainage in the subject area.

E. Abundance, distribution, and general nature of exposures of earth materials within the area.

F. Nature and source of available subsurface information. Suitable explanations should provide any technical reviewer with the means for assessing the probable reliability of such data. (Subsurface relationships can be variously determined or inferred, for example, by projection of surface features from adjacent areas, by the use of test-hole logs, and by interpretation of geophysical data, and it is evident that different sources of such information can differ markedly from one another in degree of detail and reliability according to the method used).

III. GEOLOGIC DESCRIPTIONS

The report should contain brief but complete descriptions of all natural materials and structural features recognized or inferred within the subject area. Where interpretations are added to the recording of direct observations, the bases for such interpretations should be clearly stated.

The following check list may be useful as a general, though not necessarily complete, guide for descriptions:

A. Bedrock—igneous, sedimentary, metamorphic types.

1. Identification as to rock type (e.g., granite, silty sandstone, mica schist).
2. Relative age, and, where possible, correlation with named formations (e.g.; Rincon formation, Vaqueros sandstone).
3. Distribution.
4. Dimension features (e.g.; thickness, outcrop breadth, vertical extent).
5. Physical characteristics (e.g.; color, grain size, nature of stratification, foliation, or schistosity, hardness, coherence).
6. Special physical or chemical features (e.g.; calcareous or siliceous cement, concretions, mineral deposits, alteration other than weathering).
7. Distribution and extent of weather zones; significant differences between fresh and weathered rock.
8. Response to natural surface and near-surface processes (e.g.; raveling, gullying, mass movement).

B. Structural features—stratification, foliation, schistosity, folds, zones of contortion or crushing, joints, shear zones, faults, etc.

1. Occurrence and distribution.
2. Dimensional characteristics.
3. Orientation, and shifts in orientation.
4. Relative ages (where pertinent).
5. Special effects upon the bedrock. (Describe the conditions of planar surfaces).
6. Specific features of faults (e.g.; zones of gouge and breccia, nature of offsets, timing of movements); are faults active in either the geological sense or the historical sense?

C. Surficial (unconsolidated) deposits—artificial (manmade) fill topsoil, stream-laid alluvium, beach sands and gravels, residual debris, lake and pond sediments, swamp accumulations, dune sands, marine and nonmarine terrace deposits, talus accumulations, creep and slopewash materials, various kinds of slump and slide debris, etc.

1. Distribution, occurrence, and relative age; relationships with present topography.
2. Identification of materials as to general type.
3. Dimensional characteristics (e.g. thickness, variations in thickness shape).
4. Surface expression and correlation with features such as terraces, dunes undrained depressions, anomalous protuberances.
5. Physical or chemical features (e.g. moisture content, mineral deposits content of expansible clay minerals alteration, cracks and fissures fractures).

(over

APPENDIX 2 (continued)

6. Physical characteristics (e.g.; color, grain size, hardness, compactness, coherence, cementation).
7. Distribution and extent of weathered zones; significant differences between fresh and weathered material.
8. Response to natural surface and near-surface processes (e.g.; raveling, gullying, subsidence, creep, slopewashing, slumping and sliding).

D. Drainage—surface water and roundwater.
1. Distribution and occurrence (e.g.; streams, ponds, swamps, springs, seeps, subsurface basins).
2. Relations to topography.
3. Relations to geologic features (e.g.; previous strata, fractures, faults).
4. Sources and permanence.
5. Variations in amounts of water (e.g.; intermittent springs and seeps, floods).
6. Evidence for earlier occurrence of water at localities now dry (e.g.; vegetation, mineral deposits, historic records).
7. The effect of water on the properties of the in-place materials.

E. Features of special significance (if ot already included in foregoing descripions).
1. Features representing accelerated erosion (e.g.; cliff reentrants, badlands, advancing gully heads).
2. Features indicating subsidence of settlement (e.g.; fissures, scarplets, offset reference features, historic records and measurements).
3. Features indicating creep (e.g.; fissures, scarplets, distinctive patterns of cracks and/or vegetation, topographic bulges, displaced or tilted reference features, historic records and measurements).
4. Slump and slide masses in bedrock and/or surficial deposits; distribution, geometric characteristics, correlation with topographic and geologic features, age and rates of movement.
5. Deposits related to recent floods (e.g.; talus aprons, debris ridges, canyon-bottom trash).
6. Active faults and their recent effects upon topography and drainage.

IV. THE BEARING OF GEOLOGIC FACTORS UPON THE INTENDED LAND USE

Treatment of this general topic, whether presented as a separate section or integrated in some manner with the geologic descriptions, normally constitutes the principal contribution of the report. It involves both (1) the effects of geologic features upon the proposed grading, construction, and land use, and (2) the effects of these proposed modifications upon future geological processes in the area.

The following check list includes the topics that ordinarily should be considered in submitting discussion, conclusions, and recommendations in the geologic reports:

A. General compatibility of natural features with proposed land use: Is it basically reasonable to develop the subject area?
1. Topography.
2. Lateral stability of earth materials.
3. Problems of flood inundation, erosion, and deposition.
4. Problems caused by features or conditions in adjacent properties.
5. Other general problems.

B. Proposed cuts.
1. Prediction of what materials and structural features will be encountered.
2. Prediction of stability based on geologic factors.
3. Problems of excavation (e.g.; unusually hard or massive rock, excessive flow of groundwater).
4. Recommendations for reorientation or repositioning of cuts, reduction of cut slopes, development of compound cut slopes, special stripping above daylight lines, buttressing, protection against erosion, handling of seepage water, setbacks for structures above cuts, etc.

C. Proposed masses of fill.
1. General evaluation of planning with respect to canyon-filling and sidehill masses of fill.
2. Comment on suitability of existing natural materials for fill.
3. Recommendations for positioning of fill masses, provision for underdrainage, buttressing, special protection against erosion.

D. Recommendations for subsurface testing and exploration.
1. Cuts and test holes needed for additional geologic information.
2. Program of subsurface exploration and testing, based upon geologic considerations, that is most likely to provide data needed by the soils engineer.

E. Special recommendations:
1. Areas to be left as natural ground.
2. Removal or buttressing of existing slide masses.
3. Flood protection.
4. Protection from wave erosion along shorelines.
5. Problems of groundwater circulation.
6. Position of structures with respect to active faults.

V. SEISMIC CONSIDERATIONS

The following published guidelines should be considered when preparing seismic information.
1. CDMG Note No. 37, "Guidelines to Geologic/Seismic Reports".
2. CDMG Note No. 43, "Recommended Guidelines for Determining the Maximum Credible and the Maximum Probable Earthquakes".

VI. DOCUMENTATION AND IMPLEMENTATION

A. The report should consider as the minimum requirement, Chapter 70, Uniform Building Code (1973). Refer to California Administration Code, Title 25, Section 1090, Excavation and Grading.

B. All material in the report should be relevant to the purpose of the report.

C. All statements should be documented by references or by accurate field observations.

D. Areal photos (originals or suitable copies) should be included to document any discussion on landslides and faults.

E. The method(s) of field analysis should be discussed in a lucid manner.

PYA, JES; 4/75

APPENDIX 2 (continued)

CDMG NOTE **NUMBE**

GUIDELINES FOR GEOLOGIC/SEISMIC CONSIDERATIONS IN ENVIRONMENTAL IMPACT REPORTS

The following guidelines were prepared by the Division of Mines and Geology with the cooperation of the State Water Resources Control Board to assist those who prepare and review environmental impact reports.

These guidelines will expedite the environmental review process by identifying the potential geologic problems and by providing a recognition of data needed for design analysis and mitigating measures. Al statements should be documented by reference to material (including specific page and chart numbers available to the public. Other statements should be considered as opinions and so stated.

1. *CHECKLIST OF GEOLOGIC PROBLEMS FOR ENVIRONMENTAL IMPACT REPORTS*

GEOLOGIC PROBLEMS		Could the project or a geologic event cause environmental problems?			Is this conclusion documented in attached reports?	
PROBLEM	ACTIVITY CAUSING PROBLEM	NO	YES	ENVIRONMENTAL PROBLEMS	NO	YES
EARTHQUAKE DAMAGE	Fault Movement					
	Liquefaction					
	Landslides					
	Differential Compaction Seismic Settlement					
	Ground Rupture					
	Ground Shaking					
	Tsunami					
	Seiches					
	Flooding (Failure of Dams and Levees)					
LOSS OF MINERAL RESOURCES	Loss of Access					
	Deposits Covered by Changed Land-Use Conditions					
	Zoning Restrictions					
WASTE DISPOSAL PROBLEMS	Change in Groundwater Level					
	Disposal of Excavated Material					
	Percolation of Waste Material					
SLOPE AND/OR FOUNDATION INSTABILITY	Landslides and Mudflows					
	Unstable Cut and Fill Slopes					
	Collapsible and Expansive Soil					
	Trench-Wall Stability					
EROSION, SEDIMENTATION, FLOODING	Erosion of Graded Areas					
	Alteration of Runoff					
	Unprotected Drainage Ways					
	Increased Impervious Surfaces					
LAND SUBSIDENCE	Extraction of Groundwater Gas Oil, Geothermal Energy					
	Hydrocompaction, Peat Oxidation					
VOLCANIC HAZARDS	Lava Flow					
	Ash Fall					

APPENDIX 2 (continued)

II. CHECKLIST OF GEOLOGIC REPORT ELEMENTS

REPORT ELEMENTS	yes	no
A. General Elements Present		
1. Description and map of project.	☐	☐
2. Description and map of site.	☐	☐
3. Description and map of pertinent off-site areas.	☐	☐
B. Geologic Element (refer to checklist)		
1. Are all the geologic problems mentioned?	☐	☐
2. Are all the geologic problems adequately described?	☐	☐
C. Mitigating Measures		
1. Are mitigating measures necessary?	☐	☐
2. Is sufficient geologic information provided for the proper design of mitigating measures?	☐	☐
3. Will the failure of mitigating measures cause an irreversible environmental impact?	☐	☐
D. Alternatives		
1. Are alternatives necessary to reduce or prevent the irreversible environmental impact mentioned?	☐	☐
2. Is sufficient geologic information provided for the proper consideration of alternatives?	☐	☐
3. Are all the possible alternatives adequately described?	☐	☐
E. Implementation of the Project		
1. Is the geologic report signed by a registered geologist?*	☐	☐
2. Does the report provide the necessary regulations and performance criteria to implement the project?	☐	☐

*Required for interpretive geologic information.

. *PUBLISHED REFERENCES (selected)*

California Division of Mines and Geology Publications

1 Alfors, J T . et al . 1973. Urban geology master plan for California Bulletin 198

2 Greensfelder R W . 1974 Maximum credible rock acceleration from earthquakes in California Map Sheet 23

3 Jennings, C W . 1973. Preliminary fault and geologic map Preliminary Report 13

4 Oakeshott, G B 1974. San Fernando, California earthquake of 9 February 1971 Bulletin 196

5 Note No 37 Guidelines to geologic seismic reports, 1973

6 Note No 43, Recommended guidelines for determining the maximum credible and the maximum probable earthquakes, 1975

7 Note No 44, Recommended guidelines for preparing engineering geologic reports, 1975

8 Note No 45, Recommended guidelines for preparing mine reclamation plans, 1975

B. Other Publications

1 Allen, C R et al . 1965. Relationship between seismicity and geologic structure in the southern California region Bulletin of the Seismological Society of America, v 55, no 4

2 Bolt B A and Miller, R D . 1971. Seismicity of northern and central California, 1965-1969 Bulletin of the Seismological Society of America, v 61, no 6

3 California Department of Water Resources, 1964. Crustal strain and fault movement investigation Bulletin No 116-2

4 Coffman, J L and von Hake, C A ed 1973. Earthquake history of the United States U S Department of Commerce, Publication 41-1

5 ________ ed . 1974. United States earthquakes, 1972 U S Department of Commerce

6 Hileman, J A , et al , 1973. Seismicity of the southern California region, 1 January 1932 to 31 December 1972 California Institute of Technology Contribution 2385

. *PUBLIC AGENCIES WITH GEOLOGIC DATA*

Source	Data Needed			
	Seismicity	Geology	Ground Water	Soils
braries and Geology and Engineering Departments of California Universities	x	x	x	x
alifornia Institute of Technology	x			
alifornia Division of Mines and Geology (Sacramento San Francisco, Los Angeles, CA)	x	x		
alifornia Department of Water Resources (Sacramento, CA)		x	X	x
alifornia Department of Transportation (District Offices)				x
ounty Soil & Water Conservation Districts				x
ounty Engineer and Departments of Building and Safety	x	x	x	x
ounty Highway Department				x
ounty Flood Control District				x
S Geological Survey (Menlo Park CA)	X	x	X	
S Corps of Engineers (District Engineer)		x		
S Bureau of Reclamation (Regional Offices)		x	X	
S Soil Conservation Service and Forest Service				x

PYA., JES 6/75

APPENDIX 3

Proposed Revision of Section 1931.5 of the Geothermal Regulations

At the October 28, 1974, meeting of the Geothermal Resources Board, a subcommittee made up of the State Geologist, the State Oil and Gas Supervisor, and representatives from several other State agencies was appointed to bring back to the Board recommendations for a set of realistic and strict regulations for all exploration and attendant operations within The Geysers Geothermal Resource Area. On November 13, 1974, the subcommittee held a workshop meeting at which it was decided to recommend to the Board a series of changes in Section 1931.5.

The Section now reads:

> 1931.5. If the construction of drilling sites, sumps, roads, steam transmission rights-of-way, and other construction attendant to geothermal operations could cause slumping, landslides, or unstable earth conditions, the supervisor may require that a civil engineer, geologist or engineering geologist licensed in the state and experienced in slope stability, compaction, and related problems, approve the plans and the completed construction.

The Geothermal Resources Board recommended on September 15, 1975, that Section 1931.5 be revised to read:

> 1931.5. Unstable Terrain. If the Supervisor determines that there is a hazard of slumping, landslide, or unstable earth conditions which could adversely affect the construction, maintenance, or operation of proposed drilling sites, sumps, roads, and pipelines, he shall:
>
> (a) Order that such proposed work not be commenced until the Supervisor has approved such proposed work, and
>
> (b) Require that a written analysis of the proposed work and sites therefor be submitted to the Supervisor; such analysis shall be made by a civil engineer, licensed in this State and experienced in soils engineering, and by an engineering geologist, certified in this State and experienced in slope stability and related problems, and
>
> (c) Approve such proposed work
>
> (1) If, in the Supervisor's opinion, the construction, maintenance, or operation of such proposed work will not cause or will not be adversely affected by slumping, landslides, or unstable earth conditions, or
>
> (2) If, in the Supervisor's opinion, the construction, maintenance, or operation of such proposed work is planned in such a manner as to mitigate the occurrence and the effect of slumping, landslides, or unstable earth conditions.

APPENDIX 4

BLOWOUT OF A GEOTHERMAL WELL AT THE GEYSERS GEOTHERMAL FIELD, SONOMA COUNTY, CALIFORNIA

By C. FORREST BACON,
Geologist
California Division of
Mines and Geology

On the evening of 31 March 1975 at approximately 6:45 P.M., Union Oil Company geothermal well "G.D.C." 65-28 blew out. The well, which had been on standby since its completion 7 September 1968, is located in a remote area of he Mayacmas Mountains 4 miles southeast of the main Geysers geothermal area; the blowout apparently was not witnessed.

On the day following the blowout, an oblong crater with maximum dimensions about 100 by 120 feet, had been blown out to a depth of about 20 or 25 feet. Strong peripheral cracking had developed, and slumping was taking place, stair-step fashion, around most of the perimeter. The maxmum size of the affected area was approximately 120 by 180 feet.

Steam was issuing from two sources within the crater: (1) from a 3 inch bleeder valve nipple opening on the bent-over well head, and (2) from an open hole near the former position of the well head and surface casing. A mixture of sand, dust, and rock fragments accompanied the steam venting from the open hole, but mostly clean, dry steam issued from the well head which was bent 35° to the southwest (down slope). At intervals small rock fragments were thrown as high as 150 to 200 feet in the air; 6-inch to 10-inch fragments were found scattered over much of the drill site.

This well, like over 50 percent of the wells drilled at the The Geysers, was sited on a Quaternary landslide. Since the blow-out, a great deal of time, money, and effort has been spent to regain control of the well and to try to determine whether or not the well blew out as a result of renewed movements on the old slide.

SURFACE CRACKING

Immediately following the blowout, a pair of surface cracks tangential to the crater, one somewhat arcuate and the other nearly straight, were projected to intersect on the upslope side of the well location, near the area of heaviest debris fall. The cracks, which were situated on opposite sides of the well, had been partly to completely bridged or covered by falling debris, making it difficult to trace them. The actual point of intersection could not be seen.

The time of origin and cause of these cracks are still open to question: were they the result of downslope movement of landslide materials—movement which also triggered the well casing failure and blowout—or were they merely the result of the blowout, with attendant loss of support around the crater, and perhaps also steam and water movements within the earth materials? The fact that these cracks were not aligned with the multitude of concentric slump cracks around the crater, but were tangential to those cracks, suggests that they were the result of downslope movement of landslide materials.

GROUND WATER

One factor which could have contributed to downslope movement of the slide materials is a high ground-water table. There were seeps and springs at several points near the well site. One spring was flowing from a 10 foot bank cut for the road at the upper edge of the drill site. Water was ponded along the edge of the road and a small stream flowed in the drainage ditch along the northeast edge of the drill site. Just to the west of the well was a pond and marshy area. The pond had a large water surface, about 15 feet below the level of the graded drill pad, and contained an abundance of algae. Cattails and other aquatic plants were growing around the periphery. A stream flowed into the pond from the north and subsurface springs apparently supplemented the outflow, which amounted to several gallons per minute. The pond was probably improved for use in the drilling of this well. One of the first steps taken, in the efforts to regain control of the well, was the digging of two deep drainage ditches above the well site to dewater the slopes.

GEOLOGIC RELATIONSHIPS

Geologic mapping recently completed by McLaughlin (1974) indicates that geothermal well "G.D.C." 65-28 is situated on the upper part of a large landslide nearly 1 mile long. Two other wells are sited on this same slide area and the nearest one, "Little Geysers" 2, which was drilled in 1964, was plugged and abandoned with much difficulty in 1971. Additional work is still needed on that site to seal small steam vents and a bubbling pool located in a hole on the site. A count of geothermal wells located within The Geysers area and within the bounds of McLaughlin's map area, showed that over 90 wells are located on landslides.

A preliminary geologic section drawn through the "G.D.C." 65-28 well site revealed that the 20-inch surface casing, which was set 80 feet deep, might have just barely reached in-place rock—or possibly might have been cemented in slide material. However, subsequent examination of the materials encountered in the excavation that was made around the well in the efforts to regain control, together with other evidence, indicates that the slide is at least 125 feet deep.

Information which had been published previously indicated that the hole was cased to a depth of 750 feet with

APPENDIX 4 (continued)

13$^3/_8$-inch casing. A lost string of tools at 4671 feet necessitated cementing the hole back to 1338 feet. The hole was then redrilled to 4365 feet and steam was tested at 149,000 pounds per hour (lbs/hr).

CONTROLLING THE WELL

In the effort to regain control of the blown-out well, a great bowl-shaped depression, involving removal of over 120,000 yards of material, was excavated around the well casing to a depth of approximately 82 feet. Materials encountered during the excavation included, in addition to the usual landslide debris in the upper portions, masses of intensely sheared and broken up serpentinite alternating with lenses or layers of granular to pulverulent serpentinite materials. Large blocks and chunks of firm serpentinite were found embedded in the weaker matrix materials. In some instances subhorizontal shear planes could be traced for many feet in the walls of the excavation.

Oversteepening of the walls and unsafe conditions in the excavation forced abandonment of the plan to go deep enough to reach the lowermost break in the casing and to replace all of the bent and broken parts with new casing. Instead, two steam relief systems were installed: one was slotted into the well casing near 80 feet below the original ground surface and the other was drilled down to capture steam escaping into the rock from the casing break below. New segments of casing were welded on to replace those removed during excavation and the hole was backfilled to a depth 42 feet below the ground surface. The well was "killed" or quenched by pumping in large volumes of cold water and a cement plug was installed below 160 feet.

The cause, geometry, and location of the casing failure were investigated using 1) a bore hole video camera and 2) impression mold techniques. Results showed that the 13$^3/_8$-inch casing was sheared off at approximately 125 feet below the original ground surface and was offset in a downslope direction by approximately half the casing diameter. Circumstances such as these almost certainly indicate slippage of earth materials in the old slide mass—probably moving along a plane similar to those exposed higher up in the excavation walls. On 28 July 1975 an unsuccessful attempt using hydraulic jacks, was made to retrieve the damaged portion of the casing for metallurgical tests. Similar tests run on damaged portions of casing retrieved from higher up have disclosed a low resistance to impact but no other unusual conditions.

The blown-out well was drilled using techniques and standards now outdated. Union Oil Company has initiated a program to inspect all of their early wells and to rework them to bring them up to present standards. It is hoped that other companies in the area will follow suit. However, the problem of wells sited on landslides still exists. Each wet winter season charges the slopes and slides with high moisture and causes renewed slide activity. Each winter sees reactivation of old slides at The Geysers, and quite frequently the initiation of new ones in the steep terrain of the area. It is difficult, if not impossible, to predict ahead of time which slide or potential slide will be the next to move. Remedia measures can often be taken which will help to stabilize an old slide—or to prevent a new one. However, these measures are often costly and, for some types of slides, ineffective. A careful and complete geologic investigation o each site, prepared by a professional geologist before a site is accepted, can prevent costly mistakes.

The total cost of controlling, analyzing, plugging, and abandoning well "G.D.C." 65-28 is still not known, but it is expected to be at least as high as the cost of drilling a new well. A cost-benefit analysis of 1) drilling a new well, 2) taking corrective action after a blow-out has occurred, or 3) requiring competent engineering geology analysis to preven or minimize ground failure at the well site, will come ou heavily in favor of alternative number 3.

Geothermal well "GDC" 65-28 as it appeared the day following the blowout on March 31, 1975. Steam is issuing from a 3-inch opening in the well head that was bent 35° downslope (left) and from an open hole at the right side of the steam cloud. Subsequent studies have shown that the failure may have resulted from renewed movement of the old slide on which the well was sited. The well casing was sheared at a depth 125 feet below the old ground surface.

APPENDIX 5

Recommended Certification Block for Engineering Geology and Soil Engineering Reports

It is suggested that the following signature block be included in all reports submitted by geologists or engineers:

Geological and/or soil investigations reported on herein have been conducted in accord with generally recognized and current state-of-the-art engineering geology and/or soil engineering procedures, and have been based on the intended use of the land for which geological and/or engineering services were secured.

The plans for grading herein comply with Chapter 70 of the current edition of the Uniform Building Code or an equivalent or more stringent grading ordinance. These grading plans also comply with any other soil engineering and engineering geology reports approved by the permitting agency for this site.

[*The following paragraph may be included in whole, in part, or may be added to the certification block. It allows the investigating geologist and/or soil engineer to indicate just which geologic and/or soil factors were considered in his investigation, as well as those that were not considered.*]

Slope stability, liquefaction potential, fault rupture potential [...etc.] hazards were considered in the course of this investigation. Loss of mineral resources [...etc.] was not investigated inasmuch as they were not deemed relevant to the intended land-use.

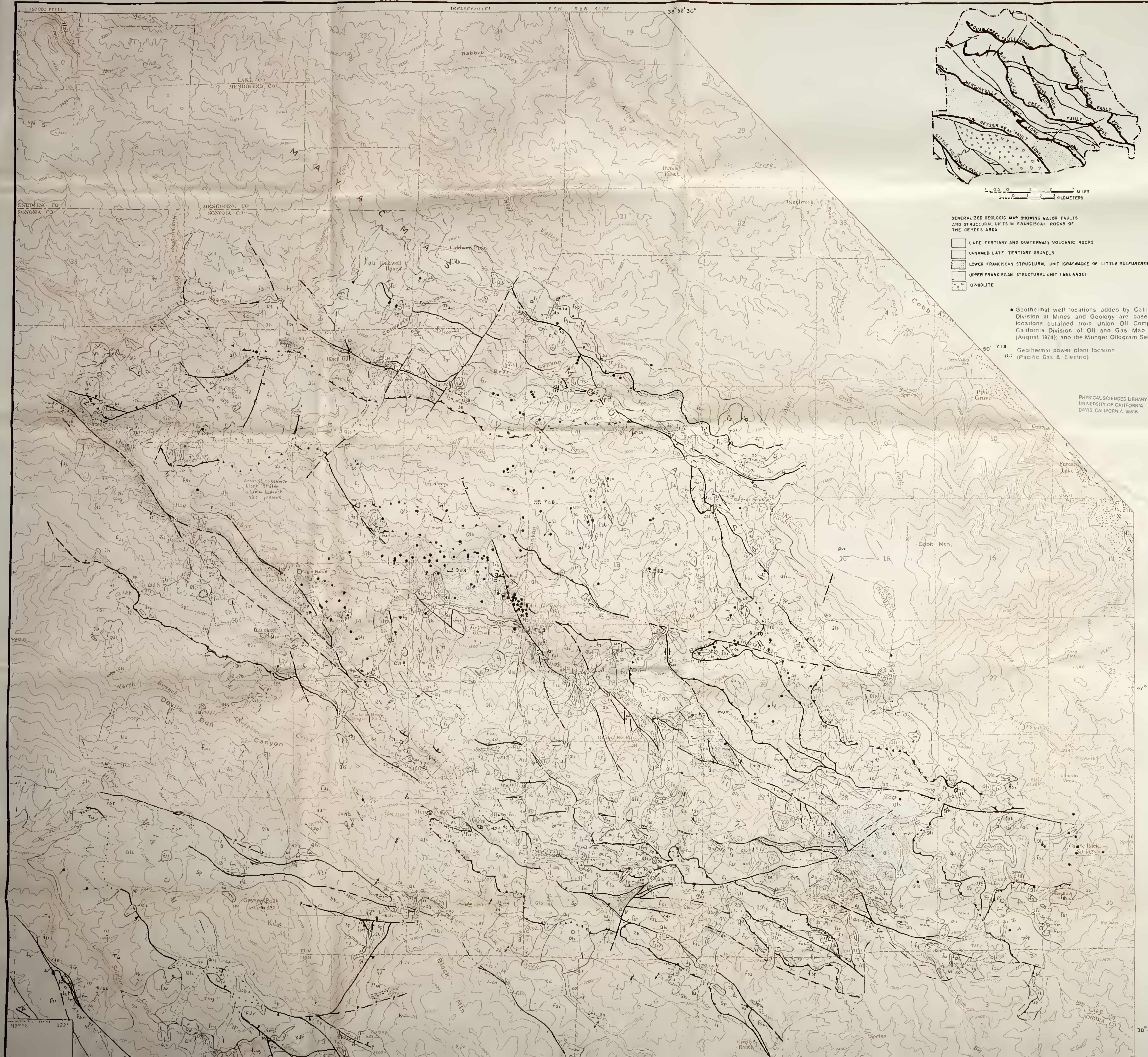
The investigations have been conducted to the best of the investigating geologist's and soil engineer's abilities in accord with the foregoing limitations.

Signature Registered Engineer	R.E. No.	Signature Registered Geologist	R.G. No.
		Certified Engineering Geologist	C.E.G. No.

1 plate
in pocket

"U.S. Geological Survey Open File Map 74-238"

Included, with permission, as Appendix 1 in California Division of Mines and Geology Special Report 122 "Engineering geology of The Geysers Geothermal Resource Area"



GENERALIZED GEOLOGIC MAP SHOWING MAJOR FAULTS AND STRUCTURAL UNITS IN FRANCISCAN ROCKS OF THE GEYERS AREA

- ▭ LATE TERTIARY AND QUATERNARY VOLCANIC ROCKS
- ▭ UNNAMED LATE TERTIARY GRAVELS
- ▨ LOWER FRANCISCAN STRUCTURAL UNIT (GRAYWACKE OF LITTLE SULFUR CREEK)
- ▭ UPPER FRANCISCAN STRUCTURAL UNIT (MELANGE)
- ▲ OPHIOLITE

● Geothermal well locations added by California Division of Mines and Geology are based on locations obtained from Union Oil Company; California Division of Oil and Gas Map G6-1 (August 1974); and the Munger Oilogram Service

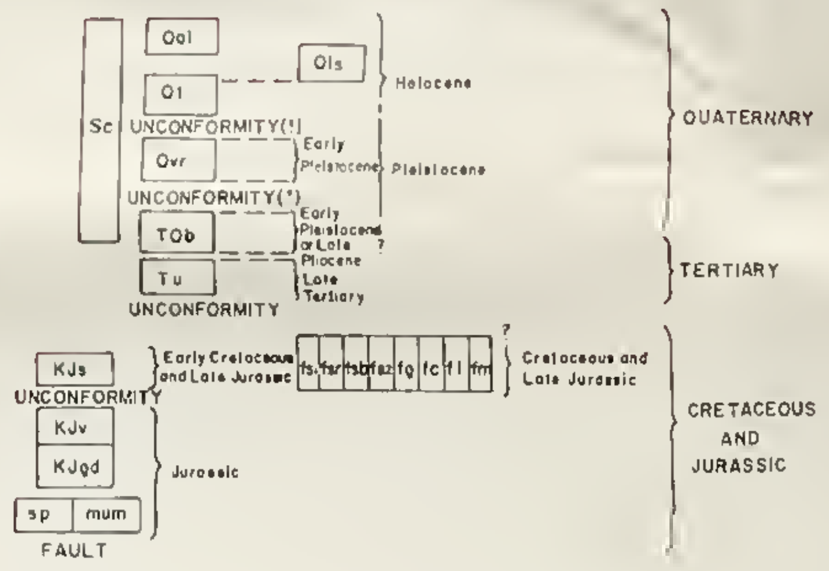
::: Geothermal power plant location (Pacific Gas & Electric)

PHYSICAL SCIENCES LIBRARY
UNIVERSITY OF CALIFORNIA
DAVIS, CALIFORNIA 95616

EXPLANATION

UNIVERSITY OF CALIFORNIA
DAVIS
APR 23 1976
GOV'T. DOCS. - LIBRARY

CORRELATION OF MAP UNITS



STRATIGRAPHY

Qal ALLUVIUM (Quaternary) Largely unconsolidated gravel, sand and clay, but locally consists of blocks up to several tens of feet in diameter. Some deposits along faults are hydrothermally altered and cemented by iron oxide, opalline silica, sulfur, calcite, and other spring deposits.

Qls LANDSLIDE DEPOSITS (Quaternary) Unconsolidated rock and soil debris, that has moved downslope by such processes as surface creep, rotational slumping, or by flowage. Headwall zones of large landslides characteristically contain closed depressions.

Qt TERRACE DEPOSITS (Quaternary) Unconsolidated to semi-consolidated older dissected alluvium containing gravel, sand, and clay derived from local bedrock source areas.

Qvr COBB MOUNTAIN RHYOLITE (Early Pleistocene) Subaerial rhyolitic and dacitic volcanic flows, tuffaceous in lower part.

sc SILICA CARBONATE ROCK (Late Tertiary and Quaternary) Composed of a mixture of magnesium carbonate minerals, quartz, opal, and chalcedony; formed by hydrothermal alteration of serpentinite; extensively developed in ultramafic rocks associated with thermal springs along major fault zones; and in many areas is the host rock for mercury deposits.

TQb CALDWELL PINES BASALT (Early Pleistocene or Late Pliocene) Subaerial Olivine basalt flows.

Tu UNNAMED GRAVELS (Late Tertiary) Non-marine pebble and cobble gravel and minor siltstone. Gravels moderately to poorly sorted, with subrounded to well-rounded clasts derived from underlying Franciscan and Great Valley sequence rocks; locally with a basal breccia composed of angular blocks up to several tens of feet in maximum dimension. Dark gray to black siltstone and mudstone in upper exposed beds locally contains ostracods, thin-shelled mollusks, and scattered fish remains. Absence of recognizable Late Cenozoic volcanic detritus suggests formation pre-dates Sonoma Group of Gealy (1951) and is perhaps Late Pliocene or older.

GREAT VALLEY SEQUENCE (Jurassic? (pre-Tithonian) - Early Cretaceous?)

KJs Knoxville Formation(?) (Late Jurassic (Tithonian) - Early Cretaceous (Valanginian)) Olive gray to black marine mudstone and thin alternating interbeds of hard dark green siltstone and graywacke sandstone, composed largely of basaltic volcanic detritus. Mudstone locally contains hard gray-weathering impure limestone concretions with rare, poorly preserved dinoflagellates of Lower Cretaceous(?) age (W. R. Evitt, written communication, 1974). Base of unit locally faulted over diabase, and coarse-grained sedimentary breccia composed chiefly of basaltic volcanic rocks is locally present at base.

KJv Basalt and diabase (Jurassic? (pre-Tithonian?)) Undifferentiated altered basaltic rocks, consisting of pillow flows, pillow breccias, tuffs, and diabase; deeply weathered except in stream bottoms, contains prominent epidote, and locally contains laumontite and prehnite.

KJgd Diabase and gabbro of Geyser Peak (Jurassic? (pre-Tithonian?)) Largely fine- to medium-grained equigranular to porphyritic diabase and gabbro. Intrusive relations of diabase and gabbro undetermined; minor basalt and quartz keratophyre locally present at the top of Geyser Peak, associated with diabase and gabbro.

ULTRAMAFIC ROCKS

Sp **sc** Serpentinite (Jurassic? (pre-Tithonian?)) Harzburgite peridotite, partly to completely altered to chrysotile± clinochrysotile±orthochrysotile, and pervasively sheared with most extensively sheared rock concentrated along margins of serpentinite bodies. Serpentinite at base of diabase and gabbro of Geyser Peak may be part of Great Valley Sequence; elsewhere serpentinite is present in Franciscan Assemblage

fsr SEDIMENTARY AND TECTONIC MELANGE (Upper Structural Unit) Mostly graywacke, shale, and conglomerate, with lesser amounts of chert, basaltic rocks, and minor blueschist, occuring chiefly as tectonic blocks and imbricated slabs from less than a foot up to several miles in length, enclosed in a pervasively sheared matrix of black shale and gouged rock. Shale matrix locally is unsheared and well bedded, and may enclose oblate limestone concretions or angular to well-rounded water worn clasts, suggesting that mélange is in part a sedimentary breccia. Components of mélange are differentiated on map as follows:

fsr Sedimentary and tectonic mélange, undifferentiated; chiefly pervasively sheared shale and gouged rock, enclosing tectonically emplaced blocks and resistant masses of rocks too small to be individually shown at map scale.

fsb Sedimentary breccia, differentiated locally; contains detritus ranging in size and roundness from angular blocks up to several tens of feet in maximum length, to well rounded pebbles less than one inch in diameter, enclosed in a matrix of tuffaceous shale or mudstone. Angular clasts are chiefly composed of radiolarian chert, basaltic volcanic breccia, talc schist or graywacke; well rounded clasts are chiefly of pebble to boulder size, and are composed of mafic and silicic porphyritic volcanic and plutonic rock, dark chert, and vein quartz; matrix material generally is sheared, but original sedimentary stratification of unit is preserved.

fs_2 Graywacke and minor interbedded shale and conglomerate with a slight to moderately strong metamorphic fabric (textural zone 1 to 2 of Blake and others, 1967). Graywacke is thin bedded to massive, relatively impervious, and fine- to medium-grained; it contains a high percentage of mafic volcanic detritus, and locally, concentrations of carbonized plant material are present along bedding planes. Interbedded conglomerate present in some areas has a graywacke matrix and contains abundant well rounded clasts of mafic and silicic porphyritic volcanic rock, diorite, dark chert, vein quartz, and quartzite, in addition to more angular clasts of basaltic volcanic rock, graywacke, and minor ultramafic rock; elsewhere conglomerate contains angular schist, radiolarian chert, and graywacke detritus identical to corresponding rock types in the Franciscan Assemblage. Graywacke of this unit contains pumpellyite±lawsonite; it is veined with quartz and calcite, and locally it is extensively hydrothermally altered.

fg Greenstone, slightly to moderately metamorphosed basaltic pillows, pillow breccias, tuffs, and diabase, slightly to extensively sheared and locally extensively hydrothermally altered.

fc Red, green, and white chert and minor interbedded siliceous tuff, thin bedded to massive, and locally hydrothermally altered; chert contains radiolaria that range in age from Late Jurassic (Tithonian) to mid-Early Cretaceous (Hauterivian)

fl Limestone; rare, foliated, and coarsely recrystallized limestone.

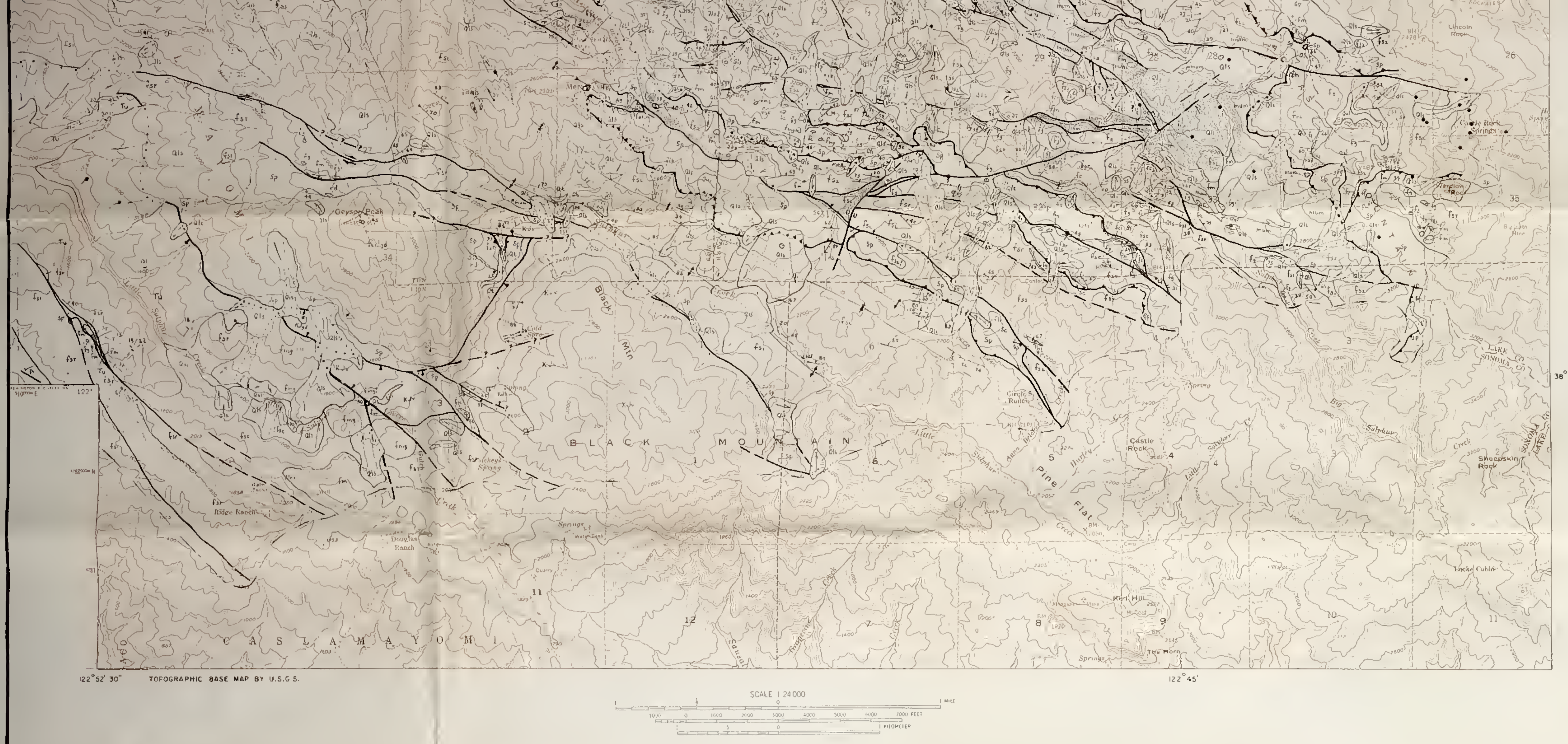
fm Blueschist grade metamorphic rocks; foliated, phyllitic to gneissose metamorphic rocks ranging in composition from Type II. to Type IV. of Coleman and Lee, 1963; containing fine to coarse grained sodic amphibole, jadeitic pyroxene, lawsonite, and other minerals formed by metamorphism at high pressures; locally, pre-metamorphic composition indicated by subscript (c) for chert, or (g) for greenstone.

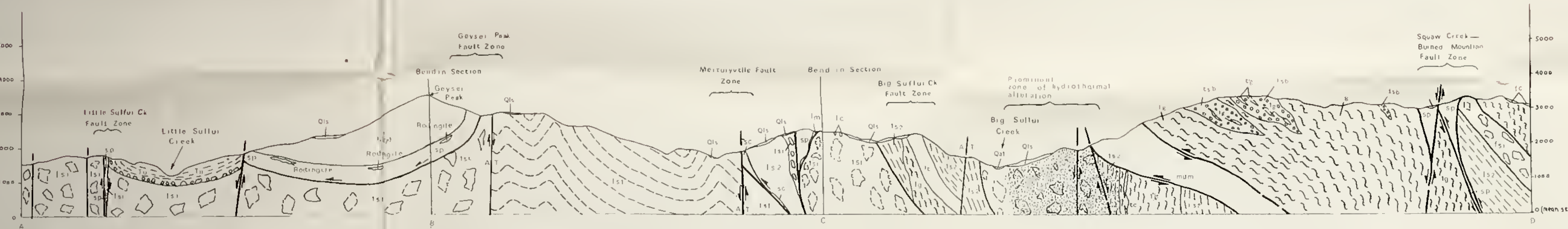
MAP SYMBOLS

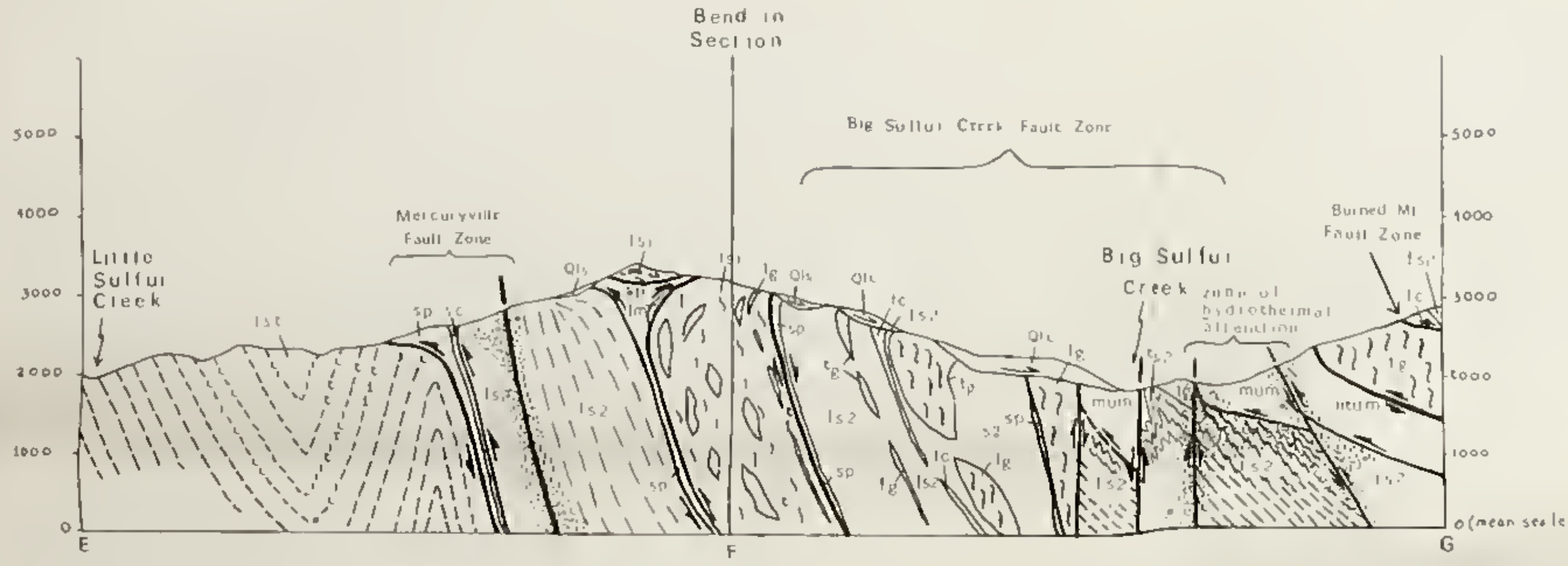
Contact
Certain to approximate location, dotted where concealed

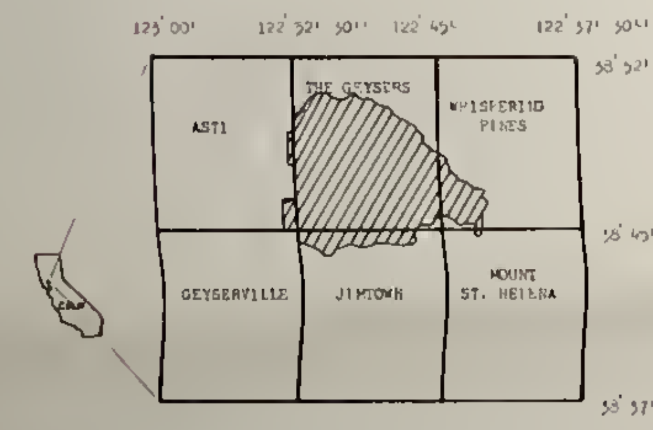
Axis of Syncline
Dashed where approximate, dotted where concealed, arrow indicates direction of plunge

Axis of Anticline
Dashed where approximate, dotted where concealed, arrow indicates direction of plunge









INDEX TO PUBLISHED U.S. GEOLOGICAL SURVEY
7 1/2-MINUTE TOPOGRAPHIC QUADRANGLES, SHOWING
LOCATION OF THE MAP AREA

APPROXIMATE MEAN DECLINATION, 1959

This map is preliminary and has not been reviewed for conformity with U.S. Geological Survey standards and nomenclature.

PHYSICAL SCIENCES LIBRARY
UNIVERSITY OF CALIFORNIA
DAVIS, CALIFORNIA 95616

and graywacke sandstone, composed largely of basaltic volcanic detritus. Mudstone locally contains hard gray-weathering impure limestone concretions with rare, poorly preserved dinoflagellates of Lower Cretaceous(?) age (W. R. Evitt, written communication, 1974). Base of unit locally faulted over diabase, and coarse-grained sedimentary breccia composed chiefly of basaltic volcanic rocks is locally present at base.

KJv Basalt and diabase (Jurassic? (pre-Tithonian?)) Undifferentiated altered basaltic rocks, consisting of pillow flows, pillow breccias, tuffs, and diabase; deeply weathered except in stream bottoms, contains prominent epidote, and locally contains laumontite and prehnite.

KJgd Diabase and gabbro of Geyser Peak (Jurassic? (pre-Tithonian?)) Largely fine- to medium-grained equigranular to porphyritic diabase and gabbro. Intrusive relations of diabase and gabbro undetermined; minor basalt and quartz keratophyre locally present at the top of Geyser Peak, associated with diabase and gabbro.

ULTRAMAFIC ROCKS

Sp **rd** Serpentinite (Jurassic? (pre-Tithonian?)) Harzburgite peridotite, partly to completely altered to chrysotile± clinochrysotile±orthochrysotile, and pervasively sheared with most extensively sheared rock concentrated along margins of serpentinite bodies. Serpentinite at base of diabase and gabbro of Geyser Peak may be part of Great Valley Sequence; elsewhere serpentinite is present in Franciscan Assemblage along major fault boundaries, shear zones, and in the cores of diapiric structures. Some evidence suggests that locally serpentinite has been re-mobilized plastically along faults of Tertiary and Quaternary age. In the Geyser Peak area, tectonic inclusions of gabbro and diabase present along serpentinite margins, are altered to rodingite mineral assemblages (rd).

mum Metamorphosed ultramafic rock (Jurassic? (pre-Tithonian?)) Foliated ultramafic rock completely metamorphosed to serpentine and calcium-magnesium amphibole mineral assemblages (antigorite±chlorite±talc-actinolite±tremolite± cummingtonite). Large ultramafic rock slab north of Big Sulfur Creek is almost completely metamorphosed to these mineral assemblages; but elsewhere metamorphosed ultramafic rock is present only locally as isolated tectonic blocks within pervasively sheared mélange units of the Franciscan Assemblage.

FRANCISCAN ASSEMBLAGE

fs_1 GRAYWACKE OF LITTLE SULFUR CREEK (Lower Structural Unit) Largely fine- to medium-grained, massive to well bedded, relatively impervious, fractured graywacke and minor interbedded black shale with slight metamorphic fabric (textural zone I of Blake and others, 1967); locally graywacke contains prominent grit-sized grains of shale, chert, and quartz and in places displays graded beds, sole marks, crossbedding, and rip-up structures; shale locally contains hard oblate impure chert and limestone concretions with black shaly rinds; the graywacke contains pumpellyite, and is veined with calcite and quartz.

ll Limestone; rare, foliated, and coarsely recrystallized limestone.

fm Blueschist grade metamorphic rocks; foliated, phyllitic to gneissose metamorphic rocks ranging in composition from Type II. to Type IV. of Coleman and Lee, 1963; containing fine to coarse grained sodic amphibole, jadeitic pyroxene, lawsonite, and other minerals formed by metamorphism at high pressures; locally, pre-metamorphic composition indicated by subscript (c) for chert, or (g) for greenstone.

MAP SYMBOLS

Contact
Certain to approximate location, dotted where concealed

Axis of Syncline
Dashed where approximate, dotted where concealed, arrow indicates direction of plunge

Axis of Anticline
Dashed where approximate, dotted where concealed, arrow indicates direction of plunge

Fault
Dashed where approximate, dotted where concealed, queried where uncertain; relative movement indicated by U (up) and D (down), by ball on downthrown side, or by arrows indicating relative lateral displacement; measured direction and amount of dip indicated by arrow and number

Thrust fault
Dashed where approximate, dotted where concealed, queried where uncertain; barbs on upper plate

Scarp line
May be either fault or landslide related; barbs on downslope side

Landslide deposit
Arrows indicate general direction of movement

Sag pond
Hot spring
Spring
Zone of hydrothermally altered rock

Attitude of planar structures

Flow structure
Bedding; tops of beds known from sedimentary structures
Bedding
Vertical beds
Overturned beds
Foliation
Strike and dip directions determined from aerial photograph
Plunge of linear features
Horizontal bedding

ACKNOWLEDGEMENTS

The cooperation of Union Oil Company, Pacific Energy Corporation, and Shell Oil Company is here acknowledged for permitting access to their lease holdings. In addition, useful background information was obtained in discussions with J. L. Moore and C. F. Isselhardt of Union Oil Company, Ian Jamieson of Pacific Energy Corporation, P. V. Storm of Shell Oil Company, J. Livingston of Geo-Logic Earth Resources, and Eugene Cioncanelli of California Geothermal Incorporated.

Some geology in the area south of Little Sulfur Creek and north of Black Mountain is modified after geology by Bailey, 1946. In addition, the map has benefited from field discussions and observations with M. C. Blake, Jr., and B. C. Hearn, and discussions with R. G. Coleman, E. H. Bailey, I. Barnes, and D. E. White of the U. S. Geological Survey.

Paleontologic support for this project has been kindly provided by E. A. Pessagno of University of Texas at Dallas, and W. R. Evitt of Stanford University.

Many landowners and residents of the map area have also been helpful in granting access to their property, and in particular, Mr. and Mrs. F. Abril, Mr. and Mrs. J. Pedroncelli, Mr. F. C. Hock, Mr. E. Pratt, and Mr. J. Kingrade are gratefully acknowledged.

REFERENCES CITED

Bailey, E. H., 1946, Quicksilver deposits of the western Mayacmas district, Sonoma County, California: Calif. Jour. Mines and Geology, v. 42, no. 3, p. 199-230.

Blake, M. C., Jr., Irwin, W. P., and Coleman, R. G., 1967, Upside-down metamorphic zonation, blueschist facies, along a regional thrust in California and Oregon: U. S. Geol. Survey Prof. Paper 575C, p. C1-C9.

Coleman, R. G., and Lee, D. E., 1963, Glaucophane-bearing metamorphic rock types of the Cazadero area, California: Jour. Petrology, v. 4, p. 260-301.

Gealy, W. K., 1951, Geology of the Healdsburg quadrangle, California: Calif. Div. Mines and Geology Bull. 161, 76 p.

PRELIMINARY GEOLOGIC MAP OF THE GEYSERS STEAM FIELD AND VICINITY, SONOMA COUNTY, CALIFORNIA

By

Robert J. McLaughlin

1974